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(71) Applicant: SCHLUMBERGER LIMITED
277 Park Avenue
New York, N.Y. 10172 (US)
(84) GB

(71) Applicant: SERVICES PETROLIERS SCHLUMBERGER
42, rue Saint-Dominique
F-75007 Paris (FR)
(84) FR

(71) Applicant: SCHLUMBERGER TECHNOLOGY B.V.
Carnegielaan 12
NL-2517 KM Den Haag (NL)
(84) DE IT

(71) Applicant: SCHLUMBERGER HOLDINGS LIMITED
P.O. Box 71, Craigmuir Chambers
Road Town, Tortola (VG)
(84) NL

(72) Inventor: Auzerais, François
120-12 Prospect Street
Ridgefield, Connecticut 06877 (US)
Inventor: Dussan, Elizabeth
19-63 Prospect Ridge
Ridgefield, Connecticut 06877 (US)

(74) Representative: Hagel, Francis et al
ETUDES ET PRODUCTIONS SCHLUMBERGER
Service Brevets B.P. 202
F-92142 Clamart Cédex (FR)

(54) **Determining horizontal and/or vertical permeability of an earth formation.**

(57) Fluid flow measurements are made *in situ* using a repeat formation tester with a modified probe aperture, or on rock samples using a mini-permeameter with a modified probe aperture. The modified probe aperture has an elongate cross-section, such as elliptic or rectangular. A first flow measurement is made with the longer dimension of the probe aperture in a first orientation (*e.g.*, horizontal or vertical) with respect to the formation bedding planes. A second flow measurement is made with the probe aperture orthogonal to the first orientation, or with a probe aperture of non-elongate (*e.g.*, circular) cross-section. Simultaneous equations relating values of known and measured quantities are solved to obtain estimates of local horizontal and/or vertical formation permeability.

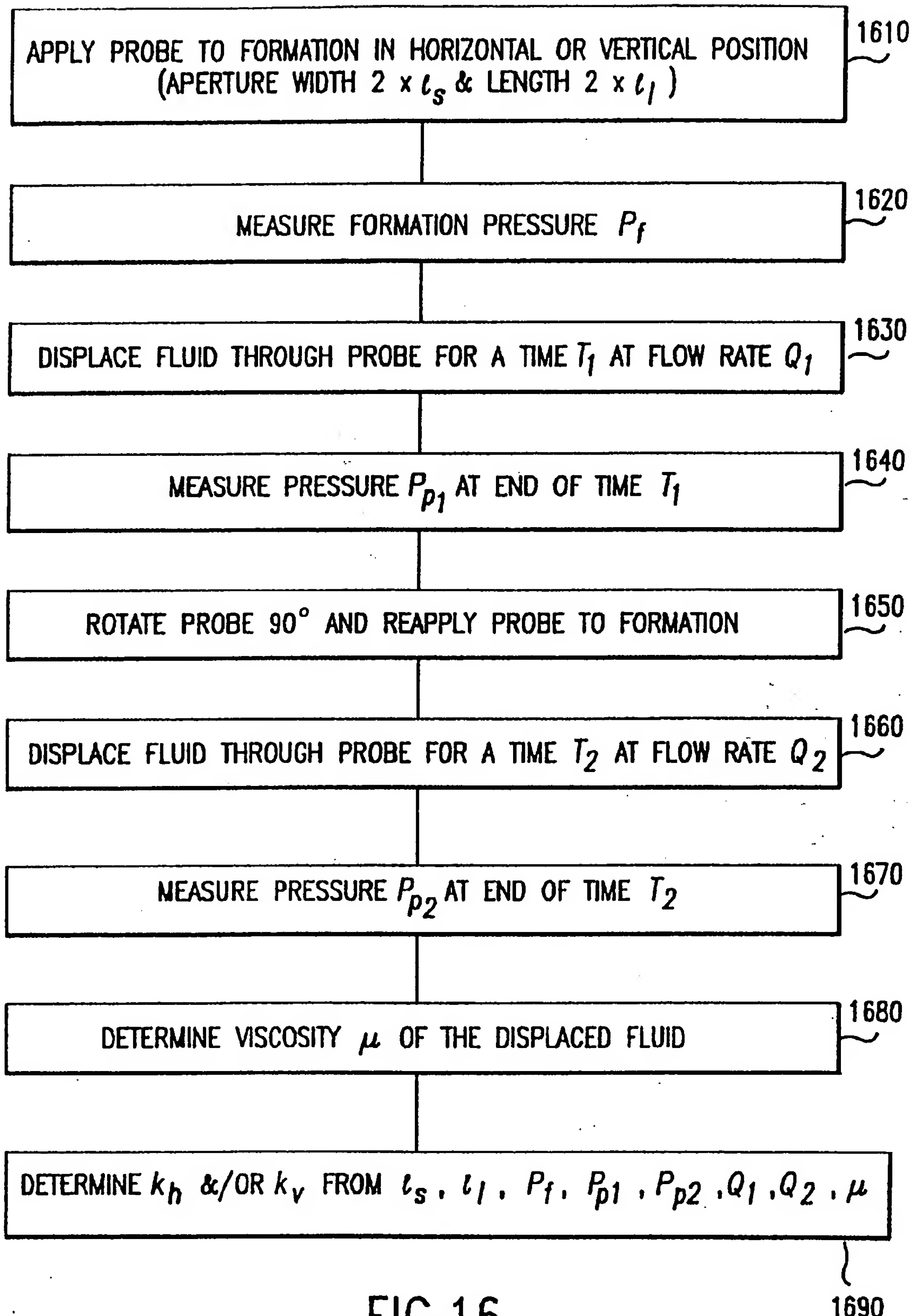

APPLY PROBE TO FORMATION IN HORIZONTAL OR VERTICAL POSITION (APERTURE WIDTH 2 x ℓ_s & LENGTH 2 x ℓ_l)
1610
MEASURE FORMATION PRESSURE P_f
1620
DISPLACE FLUID THROUGH PROBE FOR A TIME T_1 AT FLOW RATE Q_1
1630
MEASURE PRESSURE P_{p1} AT END OF TIME T_1
1640
ROTATE PROBE 90° AND REAPPLY PROBE TO FORMATION
1650
DISPLACE FLUID THROUGH PROBE FOR A TIME T_2 AT FLOW RATE Q_2
1660
MEASURE PRESSURE P_{p2} AT END OF TIME T_2
1670
DETERMINE VISCOSITY μ OF THE DISPLACED FLUID
1680
DETERMINE k_h &/OR k_v FROM ℓ_s , ℓ_l , P_f , P_{p1} , P_{p2} , Q_1 , Q_2 , μ
1690

FIG.16

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention concerns methods for estimating the horizontal and/or vertical components of permeability of an anisotropic earth formation.

2. The Prior Art

The permeability of an earth formation containing valuable resources such as liquid or gaseous hydrocarbons is a parameter of major significance to their economic production. These resources can be located by borehole logging to measure such parameters as the resistivity and porosity of the formation in the vicinity of a borehole traversing the formation. Such measurements enable porous zones to be identified and their water saturation (percentage of pore space occupied by water) to be estimated. A value of water saturation significantly less than one is taken as being indicative of the presence of hydrocarbons, and may also be used to estimate their quantity. However, this information alone is not necessarily adequate for a decision on whether the hydrocarbons are economically producible. The pore spaces containing the hydrocarbons may be isolated or only slightly interconnected, in which case the hydrocarbons will be unable to flow through the formation to the borehole. The ease with which fluids can flow through the formation, the permeability, should preferably exceed some threshold value to assure the economic feasibility of turning the borehole into a producing well. This threshold value may vary depending on such characteristics as the viscosity of the fluid. For example a highly viscous oil will not flow easily in low permeability conditions and if water injection is to be used to promote production there may be a risk of premature water breakthrough at the producing well.

The permeability of a formation is not necessarily isotropic. In particular, the permeability of sedimentary rock in a generally horizontal direction (parallel to bedding planes of the rock) may be different from, and typically greater than, the value for low in a generally vertical direction. This frequently arises from alternating horizontal layers consisting of large and small size formation particles such as different sized sand grains or clay. Where the permeability is strongly anisotropic, determining the existence and degree of the anisotropy is important to economic production of hydrocarbons.

Techniques for estimating formation permeability are known. One technique involves measurements made with a repeat formation testing tool of the type described in U.S. Patents No. 3,780,575 to Urbanosky and 3,952,588 to Whitten, such as the Schlumberger RFT™ tool. A tool of this type provides the capability for repeatedly taking two successive "pretest" samples at different flowrates from a formation via a single probe inserted into a borehole wall and having an aperture of circular cross-section. The fluid pressure is monitored and recorded throughout the sample extraction period and for a period of time thereafter. Analysis of the pressure variations with time during the sample extractions ("draw-down") and the subsequent return to initial conditions ("build-up") enables a value for an effective formation permeability to be derived for each of the draw-down and build-up phases of operation.

Figure 1 illustrates schematically the principal elements of a tool employed in taking "pretest" samples. The tip 110 of a probe is inserted through mud cake 112 into the borehole wall. Mud cake 112 and a packer 114 hydraulically seal the probe tip 110 with respect to the formation 116. The probe includes a filter 118 disposed in the probe aperture and a filter-cleaning piston 120. The pretest system comprises chambers 122 and 124 and associated pistons 126 and 128. Pistons 126 and 128 are retracted in sequence each time the probe is set. Piston 126 is withdrawn first, drawing in formation fluid at a flow rate of, for example, 50 cc/min. Then piston 128 is withdrawn, causing a flow rate of, for example, 125 cc/min. Figure 1 shows the system in mid-sequence, with piston 126 withdrawn. A strain gauge sensor 132 measures pressure in line 134 continuously during the sequence. When the probe is retracted, the pistons 126 and 128 are moved to expel the fluid, and filter cleaning piston 120 pushes debris from the probe.

The pressure measurement is recorded continuously in analog and/or digital form. Figure 2 shows a typical analog pressure recording during pretest. A pressure draw-down Δp_1 is recorded as piston 126 is withdrawn during a time period T_1, and a pressure draw-down Δp_2 is recorded as piston 128 is withdrawn during a the period T_2. When pretest chambers 122 and 124 are full (at time t_2), the pressure begins to build up over a time period Δt toward a final pressure, that of the formation.

The permeability has been estimated by analyzing the pressure recording during either buildup or drawdown. As illustrated in Figure 3, the point 310 at which the probe tip 110 is applied to the wall of the borehole 312 coincides with the center of the latter stage of the pressure disturbance during buildup. From the perspective of a coordinate system whose axes have been suitably stretched by an amount dictated by the horizontal and vertical components of the permeability, the pressure disturbance appears to be propagating spherically

outward from the probe tip 110. Thus the analysis yields a single "spherical" permeability value, consisting of a specific combination of both the horizontal and vertical components of the permeability. During drawdown, the pressure disturbance has only been analysed for the case of a homogeneous formation with isotropic permeability. For the anisotropic case, the *ad hoc* assumption has been made that the isotropic permeability be replaced by the "spherical" permeability. Only in some cases could the analysis yield separate values for horizontal and vertical permeabilities, and then only with the incorporation of data from other logging tools or from laboratory analysis of formation core samples. Until recently, it had been assumed impossible to derive separate horizontal and vertical permeability values solely from the measurements provided by the single-probe type of tool.

Another method of estimating formation permeability is described in U.S. Patent No. 4,742,459 to Lasseter. Figure 4 shows in schematic form a borehole logging device 400 useful in practicing the method. In this approach, formation pressure responses *vs.* time are measured at two observation probes (402 and 404) of circular cross-section as a transient pressure disturbance is established in the formation 406 surrounding the borehole 408 by means of a "source" probe 410. The observation probes are spaced apart in the borehole, probe 404 (the "horizontal" probe) being displaced from source probe 410 in the lateral direction and probe 402 (the "vertical" probe) being displaced from source probe 410 in the longitudinal direction. Hydraulic properties of the surrounding formation, such as values of permeability and hydraulic anisotropy, are derived from the measured pressure responses.

While the technique of this patent has advantages, the use of multiple spaced-apart probes has some inherent drawbacks. For example, the MRTT™ and MDT™ tools commercialized by Schlumberger and employing principles of the Lasseter patent have the observation probes spaced some 70 cm apart along the borehole. The estimate of vertical permeability is thus based on flow over a relatively large vertical distance. While this is sometimes appropriate, it is often preferable to obtain a more localized value of vertical permeability. If the longitudinally-spaced observation probes are set so that they straddle a hydraulic barrier in the formation (*e.g.*, a formation layer of low permeability relative to the layers in which the probes are set), the values determined for vertical permeability and hydraulic anisotropy may differ significantly from the local characteristics of the formation layers above and below the barrier. Moreover, the technique of the Lasseter patent may require simultaneous hydraulic seating of three probes, though it may be possible to make both horizontal and vertical measurements with only two probes. Accurate measurement may be prevented if one or more of the probes fails to seal properly, such as where the borehole surface is uneven. While even a single-probe system can encounter seating problems, the need for simultaneous seating of multiple probes may increase the difficulty of obtaining the desired measurement.

A method for determining the various components of the permeability of an anisotropic formation with a single probe is described in U.S. Patent No. 4,890,487 to Dussan V. *et al.* See also E.B. DUSSAN V. *et al.*, *An Analysis of the Pressure Response of A Single-Probe Formation Tester*, SPE Paper No. 16801, presented at the 62nd Annual Technical Conference and Exhibition of the Society of Petroleum Engineers (1987). Pressure draw-down and build-up are measured as fluid samples are extracted from the formation at controlled flow rates with a logging tool having a single extraction probe of circular cross-section. This may be done with a system as shown in Figure 1, producing a pressure recording as shown in Figure 2. The measured build-up and draw-down data are analyzed to derive separate values for horizontal and vertical formation permeability. This is possible because they successfully analyze the pressure disturbance during draw-down for an anisotropic formation. This technique offers a localized determination of hydraulic anisotropy, and avoids the need to incorporate data from other logging tools or core analysis. It has the disadvantage that it relies on measurement of pressure build-up, which demands an extremely fast-responding pressure transducer with a very high sensitivity. Pressure draw-down is a relatively robust measurement -- pressure is measured before and after the pressure disturbance caused by fluid extraction. Pressure build-up is a more delicate measurement because the rate of pressure recovery must be measured accurately as the detected pressure asymptotically approaches formation pressure (the pressure recovers at a rate of $1/t^{3/2}$).

A further technique for determining permeability is performed in the laboratory using formation samples and a laboratory instrument known as a mini-permeameter. The instrument has an injection probe with a nozzle of circular cross-section which is pressed against the surface of a sample and appropriately sealed. Pressurized gas flows through the injection nozzle into the rock sample as gas flow and injection pressure are measured. Referring to the schematic view of Figure 5, the process maw be performed on a first face 510 having its longitudinal (z) axis perpendicular to the bedding planes of a formation sample 500 and on a second face 520 having its longitudinal (x or y) axis parallel to the bedding planes of the formation sample. The measured lows through the sample are used in determining permeability. See, for example, R. EIJPE *et al.*, *Geological Note:Mini-Permeameters for Consolidated Rock and Unconsolidated Sand*, THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS BULLETIN, Vol. 55, No. 2, pp. 307-309 (1971); C. MCPHEE, PROPOSED MINI-

PERMEATER EVALUATION REPORT, Edinburgh Petroleum Equipment, Ltd., Edinburgh, Scotland (1987); and D. GOGGIN *et al.*. *A Theoretical and Experimental Analysis of Minipermeameter Response Including Gas Slippage and High Velocity Flow Effects*, IN SITU, 12(1&2), pp. 79-116 (1988).

Determining horizontal and/or vertical permeabilities of a formation with a mini-permeameter has a number of important limitations. The mini-permeameter is a laboratory instrument, and cannot be used to make *in situ* measurements in a well bore. Thus, it can only be used to make the necessary measurements if formation core samples are available, which is not always the case. Moreover, it entails destruction of portions of the core sample, as a smaller sample having a smooth face parallel to and perpendicular to the bedding planes must be cut from the sample for testing. Also, the mini-permeameter measures the permeability of isotropic samples. In the case of an anisotropic sample; it only gives an effective value. Thus, it would only give an effective vertical and effective horizontal permeability from the two faces 510 and 520, respectively.

SUMMARY OF THE INVENTION

It is an object of this invention to provide improved methods for determining horizontal and vertical permeabilities of an earth formation. It is further an object of the present invention to proride methods which may be performed *in situ* or at the earth's surface. Another object of the invention is to provide methods which avoid limitations of the prior art methods described above. These and other objects are attained in accordance with exemplary embodiments of the invention described below.

In a preferred embodiment, fluid low measuremenfs are made *in situ* using a repeat formation tester with a modified probe aperture, or a mini-permeameter with a modified probe aperture. The modified probe aperture has an elongate cross-section, such as elliptic or rectangular. A first flow measurement is made with the longer dimension of the probe aperture in a first orientation (*e.g.*, horizontal or vertical) with respect to the formation bedding planes. A second low measurement is made with the probe aperture orthogonal to the first orientation, or with a probe aperture of non-elongate (*e.g.*, circular) cross-section. Simultaneous equations relating values of known and measured quantities are solved to obtain estimafes of local horizontal and/or vertical formation permeability.

BRIEF DESCRIPTION OF THE DRAWING

Preferred embodiments of the invention are described in more detail below with reference to the accompanving drawing, in which:

Figure 1 illustrates schematically the principal elements of a prior-art tool employed in taking "prefest" formation fluid samples in a borehole;

Figure 2 shows a typical analog pressure recording made during pretest sampling with a tool of the type shown in Figure 1;

Figure 3 illustrates a prior-art model of a pressure disturbance in a formation;

Figure 4 illustrates schematically a prior-art borehole logging device having a source probe and a spaced-apart pair of observation probes for formation testing;

Figure 5 illustrates a formation sample used for mini-permeameter testing in accordance with the prior art;

Figure 6 illustrates generally vertical fluid flow into a horizontally-oriented, elongate probe aperture in accordance with the invention;

Figure 7 illustrates generally horizontal fluid flow into a vertically-oriented, elongate probe aperture in accordance with the invention;

Figure 8 shows a probe aperture in accordance with the invention having a cross-section of an elliptical shape of "width" 2 x ℓ_h and "length" 2 x ℓ_v ;

Figure 9 is a plot in accordance with the invention of values of formation permeability versus preferred ratios of the radius of the impermeable pad to the radius of the probe aperture for laboratory testing with a mini-permeameter.

Figure 10 is a table of values constructed in accordance with the invention for an elliptic probe aperture having an aspect ratio of 0.2 oriented vertically and horizontally;

Figure 11 is a graphic representation of the data presented in the first, second, third and sixth columns of the table of Figure 10;

Figure 12 is a graphic representation of the data presented in the first, fourth, fifth and sixth columns of the table of Figure 10;

Figure 13 is a table of values constructed in accordance with the invention for an elliptic probe aperture having an aspect ratio of 0.01 oriented vertically and horizontally;

Figure 14 is a graphic representation of the data presented in the first, second, third and sixth columns of

the table of Figure 13;

Figure 15 is a graphic represeutation of the data presented in the first. fourth, fifth and sixth columns of the table of Figure 13;

Figure 16 is a low chart of a preferred method for determining horizontal and/or vertical permeability in accordance with the invention;

Figure 17 is a flow chart of a preferred method for determining horizontal and/or vertical permeability in accordance with the invention;

Figure 18 is a table of values constructed in accordance with the invention for a rectangular probe aperture having an aspect ratio of 0.2 oriented vertically and horizontally;

Figure 19 is a graphic representation of the data presented in the firstz second third and sixth columns of the table of Figure 18;

Figure 20 is a graphic representation of the data presented in the first, fourth, fifth and sixth columns of the table of Figure 18;

Figure 21 is a table of values constructed in accordance with the invention for a circular probe aperture and an elliptic probe aperture having an aspect ratio of 0.2 oriented horizontally;

Figure 22 is a graphic representation of the data presented in the first, second, third and sixth columns of the table of Figure 21; and

Figure 23 is a graphic representation of the data presented in the first, fourth, fifth and sixth columns of the table of Figure 21.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention concerns nondestructive techniques for estimating the horizontal and/or vertical components of permeability of an anisotropic earth formation. As formations of interest typically comprise sedimentary rock, it is assumed that the formation is *isotropic* in the horizontal directions, and has a *smaller* permeability in the vertical direction than in the horizontal. For purposes of this description, the "horizontal" directions are fhose generally parallel to the bedding planes of the rock, and the "vertical" direction is generally perpendicular to the bedding planes of the rock. The term "formation" comprises a formation sample, such as a core plug taken from a borehole. In the case of a formation sample, "formation fluid" may be a liquid or a gas such as atmospheric air. It is noted that where a gas zone under consideration has been contaminated with liquid, measurements should be treated as if the formation sample is a liquid.

In accordance with the invention, flow measurements are made to obtain values from which the permeability components of an earth formation are estimated. The flow measurements may be conducted *in situ* and/or in the laboratory using formation samples. *In situ* measurements are preferably made in a borehole with a formation test tool having a probe aperture modified as described below. Formation test tools which may be employed include the Schlumberger RFT™ tester, MRTT™ tester and MDT™ tester. Laboratory measurements and measurements on outcrops are preferably made with a mini-permeameter having a probe aperture modified as described below.

The technique can be performed using a *single* probe. Pressure measurements are taken at the probe, through which fluid is forced to flow under subsfantially steady-state, single-phase conditions. For downhole measurements, the flow is preferably induced by drawing formation fluid into the tool through the probe ("draw-down"). Alternately, fluid may be injected into the formation through the probe ("injection"). Gas injection is preferred for laboratory measurements with formation samples. Whether fluid is drawn into the probe or injected out through the probe, a pressure disturbance is caused in the formation fluid.

The technique may be used to determine permeability on a length scale similar to that of the Hassler core. Thus, permeability determined by this technique should be comparable to that obtained using the recognized standard procedure in the petroleum industry.

Preferred methods of estimating horizontal and/or vertical penneability in accordance with the invention differ in at least two significant ways from the prior art methods described above. First, a probe having an aperture of *non-circular* cross-section is employed. The probe is that part of the tool or instrument in contact with the formation or formation specimen. Fluid is displaced through the probe aperture in making a measurement. The aperture is preferably shaped as a narrow slit, a small aspect ratio (width / length) being of more importance than the exact shape of the cross-section. The slit shape allows fluid to be drawn or injected in a pattem which corresponds to the direction of measurement. For example, Figure 6 shows the probe oriented horizontally. As can be seen from the flow lines in Figure 6, the fluid enters the probe (in the case of draw-down) along the vertical axis *Y*. Similarly, Figure 7 shows the ptobe oriented vertically. The flow lines in Figure 7 show the fluid entering the probe (in the case of a draw-down) along a horizontal axis *X*. The limit on the smallness of the aspect ratio results from a desire to avoid clogging, and the size of the diameter (maximum length) of the

probe. The aspect ratio as defined (width/length) is less than 1.0.

Second, measurements are taken during *two* pressure disturbances (*e.g.*, during two draw-downs), with the aperture oriented in two different directions with respect to the formation or formation specimen during the two measurements. For example, the aperture is oriented in a first direction (*e.g.*, horizontal) during a first draw-down, and is oriented in a second direction (*e.g.*, vertical) orthogonal to the first direction during a second draw-down. The "orientation" is the direction of the longest dimension of the aperture cross-section.

A number of variations are possible. For example, the non-circular aperture cross-section may be generally elliptic or rectangular or of some other elongate or slit-like form. Instead of pressure draw-downs caused by withdrawal of fluid from the formation, pressure increases caused by injection of fluid into the formation may be used. A combination of a pressure draw-down and a pressure increase (injection) may be used in place of two draw-downs. Probes with two different aperture cross-sections may be used for the two pressure disturbance (drawdown and/or injection) measurements -- for example, one of the aperture cross-sections can be circular, provided the other aperture cross-section has a small aspect ratio (ratio of width to length).

Determination of horizontal and/or vertical permeability in accordance with the preferred embodiments is based upon our derived relationship among the following parameters: the volumetric Dowrate, Q, and the viscosity, μ, of the fluid forced to pass through the aperture of the probe during draw-down or injection, the horizontal, k_h, and vertical, k_v, components of the permeability of the formation, the pressure at the probe, P_p, the pressure of the formation far from the probe (equivalent to the pressure measured by the probe when the formation fluid is in its undisturbed state), P_f, and the probe aperture dimensions $2 \times \ell_h$ and $2 \times \ell_v$. This relationship is obtained from the solution to the following boundary value problem wherein liquid is the fluid under consideration:

$$k_v \frac{\partial^2 P}{\partial z^2} + k_h \left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) = 0 \,, \qquad (1)$$

$$P = P_p \text{ at } \frac{x^2}{\ell_h^2} + \frac{z^2}{\ell_v^2} \leqq 1 \text{ and } y = 0 \,, \qquad (2)$$

$$\frac{\partial P}{\partial y} = 0 \text{ at } \frac{x^2}{\ell_h^2} + \frac{z^2}{\ell_v^2} > 1 \text{ and } y = 0 \,, \qquad (3)$$

$$P \to P_f \text{ as } x^2 + y^2 + z^2 \to \infty \text{ and } y \geqq 0 \,. \qquad (4)$$

Due to the difference in compressibility between liquid and gas, the equations for gas become:

$$k_v \frac{\partial^2 (P^2)}{\partial z^2} + k_h \left(\frac{\partial^2 (P^2)}{\partial x^2} + \frac{\partial^2 (P^2)}{\partial y^2} \right) = 0 \,, \qquad (5)$$

$$(P^2) = (P_p^2) \text{ at } \frac{x^2}{\ell_h^2} + \frac{z^2}{\ell_v^2} \leqq 1 \text{ and } y = 0 \,, \qquad (6)$$

$$\frac{\partial (P^2)}{\partial y} = 0 \text{ at } \frac{x^2}{\ell_h^2} + \frac{z^2}{\ell_v^2} > 1 \text{ and } y = 0 \,, \qquad (7)$$

$$(P^2) \to (P_f^2) \text{ as } x^2 + y^2 + z^2 \to \infty \text{ and } y \geqq 0 \,. \qquad (8)$$

P denotes the pressure field within the formation, and (x, y, z) denotes a rectangular Cartesian coordinate system oriented such that the x-axis and y-axis point in the horizontal directions and the z-axis points in the vertical direction, with the $y = 0$ surface closely approximating the location of the borehole wall near the probe and the formation occupying the domain $y \geqq 0$. In the case of the mini-permeameter, it is assumed that measurements are being made on a face of the formation sample which would satisfy these conditions if it was still in the ground. For the moment, the cross-section of the probe aperture is assumed to have an elliptical shape of "width" $2 \times \ell_h$ and "length" $2 \times \ell_v$, such as shown in Figure 8. (Examples of other possible aperture cross-sections are discussed below.) In Equation (1), the "k_v" term, $k_v(\partial^2 P/\partial z^2)$, relates to formation permeability in the vertical direction and the "k_h" term, $k_h(\partial^2 P/\partial x^2 + \partial^2 P/\partial y^2)$, relates to formation permeability in an isotropic horizonfal plane Similarly, in Equation (5) the "k_v" term relates to formation permeability in the vertical direction and the "k_h" term relates to formation permeability in an isotropic horizontal plane.

The desired relationship follows from the definition of volumetric flow rate, Q,

$$Q = \frac{k_h}{\mu} \int_{A_p} \frac{\partial P}{\partial y}\Big|_{y=0} dx\,dz \quad , \qquad (9)$$

where A_p denotes the area of the aperture of the probe. The solution to this boundary-value problem appears in J.N. GOODIER *et al.*, ELASTICITY AND PLASTICITY, John Wiley & Sons, Inc., pp. 29-35 (1958). It gives

$$K_H = \begin{cases} \dfrac{2r_p}{\pi \ell_v} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_V \ell_h^2}{K_H \ell_v^2}\right)^{1/2}\right) & \text{for } \dfrac{K_V \ell_h^2}{K_H \ell_v^2} \le 1 \\ \dfrac{2r_p K_H^{1/2}}{\pi \ell_h K_V^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_H \ell_v^2}{K_V \ell_h^2}\right)^{1/2}\right) & \text{for } \dfrac{K_V \ell_h^2}{K_H \ell_v^2} > 1 \end{cases} , \qquad (10)$$

where F denotes the complete elliptic integral of the first kind, and r_p denotes the effective probe radius, defined as

$$r_p = \sqrt{\ell_h^2/2 + \ell_v^2/2} \; . \qquad (11)$$

K_H and K_V denote the dimensionless horizontal component and the dimensionless vertical component of the permeability, respectively. For liquid:

$$K_H = \frac{4r_p(P_p - P_f)k_h}{Q\mu} \text{ and } K_V = \frac{4r_p(P_p - P_f)k_v}{Q\mu} . \qquad (12)$$

For gas:

$$K_H = \frac{4r_p[(P_p^2 - P_f^2)/2P_p]k_h}{Q\mu} \text{ and } K_V = \frac{4r_p[(P_p^2 - P_f^2)/2P_p]k_v}{Q\mu} . \qquad (13)$$

It is assumed for *in situ* measurements that the aperture cross-section is sufficiently small compared to the radius of the hole (*e.g.*, the well bore) containing the formation tester that the surface of the formation near the probe can be regarded as planar. For laboratory measurements (*e.g.*, using a mini-permeameter and a formation sample), it is assumed that an impermeable pad surrounds the probe aperture to provide a hydraulic seal between the probe tip and the sample. The size of the pad and the formation sample are assumed to be large enough to justify the no-lux boundary condition on the entire $y = 0$ surface (other than at the aperture) and the use of the semi-infinity domain (*e.g.*, the "half-space" of D. GOGGIN *et al.*, *A Theoretical and Experimental Analysis of Minipermeameter Response Including Gas Slippage and High Velocity Flow Effects*, IN SITU, 12(1&2), pp. 79-116 (1988), at Figure 1). Figure 9 plots values of permeability, k, versus preferred ratios of R_{pad}/R_{probe}, where R_{pad} is the radius of the impermeable pad and R_{probe} is the radius of the probe aperture. Pad dimensions for *in situ* measurement are less critical, in part due to the sealing effect of mud-cake at the borehole wall.

The dimensionless horizontal and vertical components of the permeability are determined as follows. Let $2 \times \ell_s$ and $2 \times \ell_l$ denote the smallest and largest dimensions of the aperture of the probe, respectively. It will be recalled that we are interested in any aperture having a small aspect ratio, i.e., the ratio ℓ_s/ℓ_l is a small number. A **vertical** orientation of the probe aperture assumes ℓ_h equals ℓ_s, and ℓ_v equals ℓ_l. A **horizontal** orientation of the probe assumes ℓ_h equals ℓ_l, and ℓ_v equals ℓ_s. It is further assumed that two drawdowns are performed. During the first drawdown fluid flows through the probe at a volumetric flowrate corresponding to Q_1, with the probe oriented vertically. During the second drawdown fluid lows through the probe at a volumetric flowrate corresponding to Q_2, with the probe oriented horizontally. It is assumed that the values of Q_1 and Q_2 are known; they need not be equal. This gives rise to the following two simultaneous equations containing only two unknowns, K_{H1} and K_{V1}:

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} > 1 \end{cases}, \quad (14)$$

and

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases}. \quad (15)$$

The subscripts 1 and 2 refer to the pressure at the probe and flow rate through the probe corresponding to the first draw-down and the second draw-down, respectively, in the definitions of K_H and K_V. The definition of the quantity M for liquid is given by:

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)}. \quad (16)$$

The definition of the quantity M for gas is given by:

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{p1}}. \quad (17)$$

The value of quantity M is readily obtained from the measured pressures and known flow rates, and is equivalent to both K_{H1}/K_{H2} and to K_{V1}/K_{V2}. The values of K_{H1} and K_{V1}, hence the values of k_h and k_v are determined from the solution to the above set of equations.

Values for K_{H1} and K_{V1} can be obtained by using a table such as Table 1 shown in Figure 10. The table is constructed from the above set of equations by evaluating the quantities M, K_{H1}, K_{V1}, K_{H2}, and K_{V2} over a range of values of the anisotropy, k_h/k_v of the formation, for a given aperture aspect ratio ℓ_s/ℓ_l. Table 1 is constructed for an elliptical aperture having aspect ratio $\ell_s/\ell_l = 0.2$ oriented vertically (subscript 1) and horizontally (subscript 2). The equation makes use of the facts that $k_h/k_v = k_{H1}/K_{V1}$, $K_{H2} = K_{H1}/M$, and the value of ℓ_s/ℓ_l is known. That is, for a selected value of k_h/k_v, equation (14) is used to evaluate K_{H1} and equation (15) is used to evaluate K_{H1}/M. The value of M is obtained by evaluating the ratio K_{H1}/K_{H2}. Finally, K_{V1} and K_{V2} are obtained by evaluating $(k_v/k_h) \times K_{H1}$ and $(k_v/k_h) \times K_{H2}$, respectively. These evaluations determine a row in the table. Additional rows of the table are obtained by repeating these evaluations for the desired range of values for k_h/k_v.

To use the table, a value of M is calculated from measured pressure values and known flow rates of a set of pretest measurements made with the probe aperture oriented in the vertical direction during a first draw-down and in the horizontal direction during a second draw-down, or *vice versa* (see equation (16) for liquids and equation (17) for gases). The values of K_{H1} and K_{V1} (or K_{H2} and K_{V2}) in the same row as the calculated value of M represent the solution to the above set of equations. For example, if ℓ_s/ℓ_l equals 0.2 and M equals 0.6732, then Table 1 (Figure 10) gives a value for K_{H1} of 1.905 and a value for K_{V1} of 0.1905. The explicit values of k_h, and k_v follow directly from the definitions of K_{H1} and K_{V1} (or K_{H2} and K_{V2}), and the known values of P_{p1}, $P_{p1} - P_f$ (or P_{p2}, $P_{p2} - P_f$), Q_1 (or Q_2), μ, and r_p (*i.e.*,

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}). \quad (18)$$

Figures 11 and 12 graphically represent the data presented in Table 1. In Figure 11, the values of the anisotropy, k_v/k_h, and the dimensionless components of the permeability, K_{H1} and K_{V1} are plotted versus values of calculated measurement factor M for an elliptic probe aperture having an aspect ratio of 0.2. The plotted values correspond to data presented in the first, second, third, and sixth colums of Table 1. The subscript 1 denotes data characterizing the vertically oriented probe. In Figure 12, the values of the anisotropy, k_v/k_h, and the dimensionless components of the permeability, K_{H2} and K_{V2}, are plotted versus values of calculated meas-

urement factor M for an elliptic probe aperture having an aspect ratio of 0.2. The plotted values correspond to data presented in the first, fourth, fifth, and sixth columns of Table 1. The subscript 2 denotes data characterizing the horizontally oriented probe. The values of the anisotropy, k_v/k_h, and the dimensionless components of the permeability, K_{H1} and K_{V1} (or K_{H2} and K_{V2}), can be determined directly from these graphs.

Table 2 (Figure 13) gives values for an elliptic aperture having an aspect ratio ℓ_s/ℓ_l of 0.01 oriented vertically and horizontally. The data of Table 2 is presented graphically in Figures 14 and 15. In Figure 14, the values of the anisotropy, k_v/k_h, and the dimensionless comronents of the permeability, K_{H1} and K_{V1}, are plotted versus values of calculated measurement factor M for an elliptic probe aperture having an aspect ratio of 0.01. The plotted values correspond to data presented in the first, second, third, and sixth columns of Table 2. The subscript 1 denotes data characterizing the vertically oriented probe. In Figure 15, the values of the anisotropy, k_v/k_h, and the dimensionless components of the permeability, K_{H2} and K_{V2}, are plotted versus values of calculated measurement factor M for an elliptic probe aperture having an aspect ratio of 0.01. The plotted values correspond to data presented in the first, fourth, fifth, and sixth columns of Table 1. The subscript 2 denotes data characterizing the horizonfally oriented probe. The values of the anisotropy, k_v/k_h, and the dimensionless components of the permeability, K_{H1} and K_{V1} (or K_{H2} and K_{V2}), can be determined directly from these graphs.

It is also rather straight-forward to determine the propagation of error from the measured quantity M to the predicfed quantifies k_h and k_v. If there is a ±10% error in M, then the range of possible values of K_H and K_V corresponds to their values in rows bracketed by M equal to 1.1 x M and 0.9 x M. For example, if ℓ_s/ℓ_l equals 0.2 and M equals 0.67, then Table 1 (Figure 10) gives for the *vertical* probe $177 \leqq K_{H1} \leqq 2.07$, or, 1.92 ± 7.6% error, and $0.97 \leqq K_{V1} \leqq 0.32$, or, 0.21 ± 54% error, and for the *horizontal* probe $2.38 \leqq K_{H2} \leqq 3.42$, or 2.90 ± 17.8% error, and $0.17 \leqq K_{V2} \leqq 0.44$, or, 0.31 ± 43% error. In this case, the most accurate determination of K_H and K_V is obtained using the results from the vertical probe for K_H and the horizontal probe for K_V.

When the aspect ratio of the probe aperture *decreases* in value, the error propagated also *decreases*. For examples, if ℓ_s/ℓ_l equals 0.01 and M equals 0.47 (corresponding to the same anisotropy as in the previous example), then Table 2 (Figure 13) gives for the *vertical* probe $3.15 \leqq K_{H1} \leqq 3.30$, or, 3.22 ± 2.2% error, and $0.24 \leqq K_{V1} \leqq 0.43$, or, 0.33 ± 29.3% error, and for the *horizontal* probe $6.20 \leqq K_{H2} \leqq 7.88$, or 7.04 ± 11.9% error, and $0.56 \leqq K_{V2} \leqq 0.83$, or, 0.70 ± 19% error. Again, the most accurate determination of K_H and K_V consists of using the results from the vertical probe for K_H and the horizontal probe for K_V. Note the improvemenf in accuracy by using a probe with a smaller aspect ratio.

Flow charts of preferred methods in accordance with the invention are given in Figures 16 and 17. The probe is applied to the formation (or formation sample) with the aperture oriented in a first direction, preferably either horizontal or vertical (step 1610). The formation pressure is measured at the probe (step 1620). Muid is displaced through the probe for a first time period at a flow rate Q_1 (step 1630). Pressure at the probe is measured at the end of the first time period (step 1640). The probe is then withdrawn, rotated 90°, and reapplied to the formation (step 1650). Fluid is displaced through the probe for a second time period at a flow rate Q_2 (step 1660). Pressure at the probe is measured at the end of the second time period (step 1670). Viscosity of the fluid is measured (step 1680). Values of horizontal permeability k_h and/or k_v, are determined from the aperture dimensions, the measured pressures, the low rates, and the fluid viscosity.

A preferred embodiment of determining horizontal and/or vertical permeability values (*e.g.*, of performing step 1690) is shown in Figure 17. Values are obtained for the aperture dimensions, the measured pressures, the flow rates, and the fluid viscosity, such as by the method of Figure 16 (step 1710). A value for measurement factor M is calculated using the measured pressures and the flow rates (step 1720). Permeability factors K_{H1} and K_{V1} (or K_{H2} and K_{V2}) are evaluated using the aperture dimensions and the value for measurement factor M (step 1730). Values of k_h and/or k_v, are determined from the permeability factors, the aperture dimensions, the measured pressures, one or both of the flow rates, Q_1 and Q_2, and the fluid viscosity.

The steps of Figures 16 and 17 need not be carried out in the precise order given. For example, the formation pressure may be measured at the probe at any suitable stage in the process, or may be measured at a separate probe. The viscosity of the displaced fluid may be determined at any time prior to determining values for k_h and/or k_v, by testing of a sample or by estimation or ofherwise.

Other aperfure shapes may be used, such as that of a rectangle. For this case an approximate solution to the boundary value problem has been obtained. Instead of assuming that the pressure of the fluid takes on a constant value at the aperture, it is assumed that the velocity of the fluid leaving the formation is the same at every point of the aperture. Expressions have been derived relating Q, μ, k_h, k_v, and $\overline{P}_p - P_f$ for the probe oriented both vertically and horizontally with respecf to the formation (formation sample) with an aperture having dimensions $2 \times \ell_s$ by $2 \times \ell_l$, where $\overline{P}_p$ denotes the average pressure over the aperture (see H.S. CARSLAW *et al.*, CONDUCTION OF HEAT IN SOLIDS, Oxford Science Publications (1959)). They are

$$K_{H_1} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_s^2}{\ell_l^2}\right)}\left\{\frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s}\sinh^{-1}\frac{K_{V_1}^{1/2}\ell_s}{K_{H_1}^{1/2}\ell_l} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s} + \frac{K_{V_1}^{1/2}\ell_s}{3K_{H_1}^{1/2}\ell_l}\left[1 + \frac{K_{H_1}^{3/2}\ell_l^3}{K_{V_1}^{3/2}\ell_s^3} - \left(1 + \frac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{3/2}\right]\right\}, \quad (19)$$

$$\frac{K_{H_1}}{M} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_l^2}{\ell_s^2}\right)}\left\{\frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l}\sinh^{-1}\frac{K_{V_1}^{1/2}\ell_l}{K_{H_1}^{1/2}\ell_s} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l} + \frac{K_{V_1}^{1/2}\ell_l}{3K_{H_1}^{1/2}\ell_s}\left[1 + \frac{K_{H_1}^{3/2}\ell_s^3}{K_{V_1}^{3/2}\ell_l^3} - \left(1 + \frac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{3/2}\right]\right\}, \quad (20)$$

where the definitions of K_{H1}, K_{V1}, K_{H2}, K_{V2}, M and r_p are the same as in the case of the elliptically-shaped aperture, with the exception that $\overline{P}_p - P_f$ takes the place of $P_p - P_f$. For liquids:

$$K_{H1} = \frac{4r_p(P_{p1} - P_f)k_h}{Q_1\,\mu}; \; K_{V1} = \frac{4r_p(P_{p1} - P_f)k_v}{Q_1\,\mu}; \quad (21)$$

$$K_{H2} = \frac{4r_p(P_{p2} - P_f)k_h}{Q_2\,\mu}; \; K_{V2} = \frac{4r_p(P_{p2} - P_f)k_v}{Q_2\,\mu}; \quad (22)$$

and

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)}. \quad (23)$$

For gases:

$$K_{H1} = \frac{4r_p[(P_{p1}^2 - P_f^2)/2P_{p1}]k_h}{Q_1\,\mu}; \; K_{V1} = \frac{4r_p[(P_{p1}^2 - P_f^2)/2P_{p1}]k_v}{Q_1\,\mu}; \quad (24)$$

$$K_{H2} = \frac{4r_p[(P_{p2}^2 - P_f^2)/2P_{p2}]k_h}{Q_2\,\mu}; \; K_{V2} = \frac{4r_p[(P_{p2}^2 - P_f^2)/2P_{p2}]k_v}{Q_2\,\mu}; \quad (25)$$

and

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{p1}}. \quad (26)$$

Simultaneous equations (19) and (20) can be solved using the same technique as before. For example, the variables M, K_{H1}, K_{V1}, K_{H2}, and K_{V2} have been evaluated over a range of values of k_h/k_v for a rectangular aperture with aspect ratio equal to 0.2. The data are given in Table 3 of Figure 18, and presented graphically in Figures 19 and 20. Note the similarity between Table 1 (Figure 10) and Table 3 (Figure 18).

Probe apertures of different shapes may be used for the two pressure disturbance measurements (*e.g.*, draw-downs). One of the two probe apertures may be circular. For example, assume that probe 1 has a circular aperture of radius r_{p1} and that probe 2 has an elliptical aperture of known aspect ratio ℓ_s/ℓ_l oriented **horizontally** with respect to the formation (or formation sample). The relevant relationships follow from the results for the elliptical aperture. They are

$$K_{H_1} = \frac{2}{\pi}\,F\left(\frac{\pi}{2}, \sqrt{1 - \frac{K_{V_1}}{K_{H_1}}}\right) \quad (27)$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_{p_1}}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \le 1 \\ \dfrac{2r_{p_2}K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases} \quad (28)$$

For liquids:

$$K_{H1} = \frac{4r_{p1}(P_{p1} - P_f)k_h}{Q_1\mu}; \qquad K_{V1} = \frac{4r_{p1}(P_{p1} - P_f)k_v}{Q_1\mu}; \quad (29)$$

$$K_{H2} = \frac{4r_{p2}(P_{p2} - P_f)k_h}{Q_2\mu}; \qquad K_{V2} = \frac{4r_{p2}(P_{p2} - P_f)k_v}{Q_2\mu}. \quad (30)$$

For gases:

$$K_{H1} = \frac{4r_{p1}[(P_{p1}^2 - P_f^2)/2P_{p1}]k_h}{Q_1\mu}; \qquad K_{V1} = \frac{4r_{p1}[(P_{p1}^2 - P_f^2)/2P_{p1}]k_v}{Q_1\mu}; \quad (31)$$

$$K_{H2} = \frac{4r_{p2}[(P_{p2}^2 - P_f^2)/2P_{p2}]k_h}{Q_2\mu}; \qquad K_{V2} = \frac{4r_{p2}[(P_{p2}^2 - P_f^2)/2P_{p2}]k_v}{Q_2\mu}. \quad (32)$$

The value r_{p2}, for the elliptical aperture is given by:

$$r_{p2} = \sqrt{\ell_s^2/2 + \ell_l^2/2} \quad (33)$$

A solution to simultaneous equations 27 and 28 can be obtained using the same method as described in the aboye examples. Table 4 of Figure 21 contains evaluations of M, K_{H1}, K_{V1}, K_{H2}, and K_{V2} over a range of values of k_h/k_v for the case of a circular aperture and a horizontal elliptical aperture with aspect ratio ℓ_s/ℓ_l equal to 0.2. These results are illustrated graphically in Figures 22 and 23.

While the foregoing describes and illustrates particular preferred embodiments of the invention, it will be understood that many modifications may be made without departing from the spirit of the invention. For example, it may be possible to use a first elongate shaped probe having width $2 \times \ell_{s1}$ and length ℓ_{l1}. Then, dig the second sampling in an orthogonal, second direction, a second elongate probe having width $2 \times \ell_{s2}$ and length ℓ_{l2} is used. The two probes may differ in their overall dimensions. However, the mathematical interpretafion is equivalent. The preferred embodiment presumes that the dimensions are the same for simplicity. Also, it may be possible to have a rectangular shaped probe instead of the elliptical shaped probe during the second sampling, while having a circular probe during the first sampling or *vice versa*. We intend the following claims to cover any such modifcations as fall within the true spirit and scope of the invention.

Claims

1. A method of estimating permeability of an et formation in at least one of two orthogonal directions, the formation containing a formation fluid, comprising the steps of:
   a. measuring a pressure P_f of the formation fluid;
   b. creating a pressure disturbance in the formation fluid by displacing fuid through a probe aperture for a first time period at a first flow rate Q_1, the probe aperture having an elongate cross-section of width $2 \times \ell_s$ and length $2 \times \ell_l$ and being oriented in a first direction;
   c. measuring a pressure P_{p1} of the fluid substantially at the end of the first time period;
   d. creating a pressure disturbance in the formation fluid by displacing fluid through a probe aperture for a second The period at a second rate Q_2, the probe aperture having an elongate cross-section of width $2 \times \ell_s$ and length $2 \times \ell_l$ and being oriented in a second direction orthogonal to said first direction;
   e. measuring a pressure P_{p2} of the fluid substantially at the end of the second time period;
   f. determining a value μ for viscosity of fluid in the formation; and
   g. determining a value of permeability in at least one of said first and second directions from the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, at least one of measured pressures P_{p1} and P_{p2}, at least one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

2. The method of claim 1. wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and form the flow rate Q_1 and Q_2 ;
ii. determining a value of dimensionless quantity K_{Hl} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_V representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture length $2 \times \ell_s$ and the aperture lenght $2 \times \ell_l$; and
iii. determining a horizontal permeability value k_h from the values of quantity K_{Hl}, the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, at least one of measured pressures P_{p1} and P_{p2} , at least one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

3. The method of claim 1, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$ in accordance with the relationships .

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} \leq 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_l^2}{K_{V_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} > 1 \end{cases},$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} \leq 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_s^2}{K_{V_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} > 1 \end{cases},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;
iii. determining a horizontal permeability value k_h from the values of a quantity K_{Hl} comprising one of the quantities K_{H1} and K_{H1}/M, the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Hl} = \frac{4r_p(P_{p1} - P_f)k_h}{Q_n \mu},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\ .$$

4. The method of claim 1, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation based on the calculated measurement factor M and the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$ in accordance with the relationships

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} > 1 \end{cases},$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\ ;$$

where F denotes the complete elliptic integral of the first kind;
iii. determining a horizontal permeability value k_h from the values of quantity K_{H1}, the aperture with $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, the measured pressure P_{p1}, the flow rate Q_1, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{H1} = \frac{4r_p(P_{p1} - P_f)k_h}{Q_1\,\mu},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\ .$$

5. The method of claim 1, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture width $2 \times \ell_s$ and the

aperture length 2 x ℓ_l in accordance with the relationships

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_s^2}{K_{H_1}\ell_l^2} > 1 \end{cases},$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a vertical permeability value k_v from the values of a quantity K_{vl} comprising one of quantities K_{V1} and K_{V1}/M, the apeture width 2 x ℓ_s and the aperture length 2 x ℓ_l, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Hl} = \frac{4r_p(P_{pj} - P_f)k_v}{Q_n \mu},$$
$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

6. The method of claim 1, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{pt}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture width 2 x ℓ_s and the aperture length 2 x ℓ_l in accordance with the relationships

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_l^2}{K_{V_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} > 1 \end{cases},$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_s^2}{K_{V_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} > 1 \end{cases},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a horizontal permeability value k_h from the values of a quantity K_{Hl} comprising one of the quantities K_{H1} and K_{H1}/M, the aperture width 2 x ℓ_s and the aperture length 2 x ℓ_l, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Hl} = \frac{4r_p[(P_{pj}^2 - P_f^2)/2P_{pj}]k_h}{Q_n\,\mu},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

7. The method of claim 1, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{p1}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture width 2 x ℓ_s and the aperture length 2 x ℓ_l in accordance with the relationships

$$K_{H_1} = \begin{cases} \dfrac{2r_p}{\pi \ell_l} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_s K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_l^2}{K_{V_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_s^2}{K_{H_1} \ell_l^2} > 1 \end{cases},$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_p}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} \le 1 \\ \dfrac{2r_p K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_s^2}{K_{V_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} > 1 \end{cases},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a vertical permeability value k_v from the values of quantity K_{Vi} comprising one of quantities K_{V1} and K_{V1}/M, the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, a measured pressure P_{pi} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Vi} = \frac{4r_p[(P_{pi}^2 - P_f^2)/2P_{pi}]k_v}{Q_n \mu},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

8. A method of estimating permeability of an earth formation in at least one of two orthogonal directions, comprising the steps of:

a. measuring a pressure P_f of fluid in the formation;

b. creating a pressure disturbance in the formation fluid by displacing fluid through a probe aperture for a first time period at a first flow rate Q_1, the probe aperture having an elongate cross-section of width $2 \times \ell_s$ and length $2 \times \ell_l$ and being oriented in a first direction;

c. measuring pressure of the fluid substantially at the end of the first period to obtain a value $\overline{P}_{p1}$ of average pressure over the aperture;

d. creating a pressure disturbance in the formation fluid by displacing fluid through a probe aperture for a second time period at a second rate Q_2, the probe aperture having an elongate cross-section of width $2 \times \ell_s$ and length $2 \times \ell_l$ and being oriented in a second direction orthogonal to said first direction;

e. measuring pressure of the fluid substantially at the end of the second time period to obtain a value $\overline{P}_{p2}$ of average pressure over the aperture;

f. determining a value μ for viscosity of fluid in the formation; and

g. determining a value of permeability in at least one of two orthogonal directions from the aperture width $2 \times \ell_s$ and the aperture length $2 \times \ell_l$, the measured pressure P_f, at least one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, at least one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

9. The method of claim 8, wherein step g. comprises the steps of:
i. calculating a measurememt factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2;
ii. determining a value of a dimensionless quantity K_{Hl} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_V representative of the vertical permeability of the formation. based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$;
iii. determining a horizontal permeability value k_h from the values of quantity K_{Hl}, the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$, the measured pressure P_f, at least one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, at least one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

10. The method of claim 8, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2;
ii. determining a value of a dimensionless quantity K_H representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{Vl} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$;
iii. determining a vertical permeability value k_v from the values of quantity K_{Vl}, the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$, the measured pressure P_f, at least one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, at least one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

11. The method of claim 8, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$ in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_s^2}{\ell_l^2}\right)} \left\{ \frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s} \sinh^{-1}\frac{K_{V_1}^{1/2}\ell_s}{K_{H_1}^{1/2}\ell_l} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s} + \frac{K_{V_1}^{1/2}\ell_s}{3K_{H_1}^{1/2}\ell_l}\left[1 + \frac{K_{H_1}^{3/2}\ell_l^3}{K_{V_1}^{3/2}\ell_s^3} - \left(1 + \frac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{3/2}\right]\right\},$$

$$\frac{K_{H_1}}{M} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 - \frac{\ell_l^2}{\ell_s^2}\right)} \left\{ \frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l} \sinh^{-1}\frac{K_{V_1}^{1/2}\ell_l}{K_{H_1}^{1/2}\ell_s} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l} + \frac{K_{V_1}^{1/2}\ell_l}{3K_{H_1}^{1/2}\ell_s}\left[1 + \frac{K_{H_1}^{3/2}\ell_s^3}{K_{V_1}^{3/2}\ell_l^3} - \left(1 + \frac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{3/2}\right]\right\};$$

iii. determining a horizontal permeability value k_h from the value of a quantity K_{Hj} comprising one of the values K_{H1} and K_{H1}/M, the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$, the measured pressure P_f, a pressure value $\overline{P}_{pj}$ comprising one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, a flow rate Q_n comprising one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Hl} = \frac{4r_p[(P_{pj} - P_f)k_h}{Q_n\,\mu},$$
$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

12. The method of claim 8, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$ in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_s^2}{\ell_l^2}\right)}\left\{\frac{K_{H_1}{}^{1/2}\ell_l}{K_{V_1}{}^{1/2}\ell_s}\sinh^{-1}\frac{K_{V_1}{}^{1/2}\ell_s}{K_{H_1}{}^{1/2}\ell_l} + \sinh^{-1}\frac{K_{H_1}{}^{1/2}\ell_l}{K_{V_1}{}^{1/2}\ell_s} + \frac{K_{V_1}{}^{1/2}\ell_s}{3K_{H_1}{}^{1/2}\ell_l}\left[1 + \frac{K_{H_1}{}^{3/2}\ell_l^3}{K_{V_1}{}^{3/2}\ell_s^3} - \left(1 + \frac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{3/2}\right]\right\},$$

$$\frac{K_{H_1}}{M} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_l^2}{\ell_s^2}\right)}\left\{\frac{K_{H_1}{}^{1/2}\ell_s}{K_{V_1}{}^{1/2}\ell_l}\sinh^{-1}\frac{K_{V_1}{}^{1/2}\ell_l}{K_{H_1}{}^{1/2}\ell_s} + \sinh^{-1}\frac{K_{H_1}{}^{1/2}\ell_s}{K_{V_1}{}^{1/2}\ell_l} + \frac{K_{V_1}{}^{1/2}\ell_l}{3K_{H_1}{}^{1/2}\ell_s}\left[1 + \frac{K_{H_1}{}^{3/2}\ell_s^3}{K_{V_1}{}^{3/2}\ell_l^3} - \left(1 + \frac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{3/2}\right]\right\};$$

iii. determining a vertical permeability value k_v from the values of a quantity K_{Vj} comprising one of quantities K_{V1} and K_{V1}/M, the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$, the measured pressure P_f, a pressure value $\overline{P}_{pj}$ comprising one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, a flow rate Q_n comprising one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{vl} = \frac{4r_p(P_{pj} - P_f)k_v}{Q_n\,\mu},$$
$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

13. The method of claim 8, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(\overline{P}_{p1}{}^2 - P_f^2)\overline{P}_{p2}}{Q_1(\overline{P}_{p2}{}^2 - P_f^2)\overline{P}_{p1}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions 2 x ℓ_s and 2 x ℓ_l in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_s^2}{\ell_l^2}\right)}\left\{\frac{K_{H_1}{}^{1/2}\ell_l}{K_{V_1}{}^{1/2}\ell_s}\sinh^{-1}\frac{K_{V_1}{}^{1/2}\ell_s}{K_{H_1}{}^{1/2}\ell_l} + \sinh^{-1}\frac{K_{H_1}{}^{1/2}\ell_l}{K_{V_1}{}^{1/2}\ell_s} + \frac{K_{V_1}{}^{1/2}\ell_s}{3K_{H_1}{}^{1/2}\ell_l}\left[1 + \frac{K_{H_1}{}^{3/2}\ell_l^3}{K_{V_1}{}^{3/2}\ell_s^3} - \left(1 + \frac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{3/2}\right]\right\},$$

$$\frac{K_{H_1}}{M} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_l^2}{\ell_s^2}\right)}\left\{\frac{K_{H_1}{}^{1/2}\ell_s}{K_{V_1}{}^{1/2}\ell_l}\sinh^{-1}\frac{K_{V_1}{}^{1/2}\ell_l}{K_{H_1}{}^{1/2}\ell_s} + \sinh^{-1}\frac{K_{H_1}{}^{1/2}\ell_s}{K_{V_1}{}^{1/2}\ell_l} + \frac{K_{V_1}{}^{1/2}\ell_l}{3K_{H_1}{}^{1/2}\ell_s}\left[1 + \frac{K_{H_1}{}^{3/2}\ell_s^3}{K_{V_1}{}^{3/2}\ell_l^3} - \left(1 + \frac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{3/2}\right]\right\};$$

iii. determining a horizontal permeability value k_h from the value of a quantity K_{Hi} comprising one of values K_{H1} and K_{H1}/M, the aperture dimensions 2 x ℓ_s and 2 x ℓ_l, the measured pressure P_f, a pressure value $\overline{P}_{pj}$ comprising one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, a flow rate Q_n comprising one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Hi} = \frac{4r_p[(\overline{P}_{pj}^2 - P_f^2)/2\overline{P}_{p1}]k_h}{Q_n\,\mu},$$

$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}.$$

14. The method of claim 8, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressure P_f, the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, and the flow rates Q_1 and Q_2 in accordance with relationship

$$M = \frac{Q_2(\overline{P}_{p1}{}^2 - P_f^2)\overline{P}_{p2}}{Q_1(\overline{P}_{p2}{}^2 - P_f^2)\overline{P}_{p1}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions 2 x ℓ_s and 2 x ℓ_l in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_s^2}{\ell_l^2}\right)}\left\{\frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s}\sinh^{-1}\frac{K_{V_1}^{1/2}\ell_s}{K_{H_1}^{1/2}\ell_l} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_l}{K_{V_1}^{1/2}\ell_s} + \frac{K_{V_1}^{1/2}\ell_s}{3K_{H_1}^{1/2}\ell_l}\left[1 + \frac{K_{H_1}^{3/2}\ell_l^3}{K_{V_1}^{3/2}\ell_s^3} - \left(1 + \frac{K_{H_1}\ell_l^2}{K_{V_1}\ell_s^2}\right)^{3/2}\right]\right\},$$

$$\frac{K_{H_1}}{M} = \frac{2}{\pi}\sqrt{\frac{1}{2}\left(1 + \frac{\ell_l^2}{\ell_s^2}\right)}\left\{\frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l}\sinh^{-1}\frac{K_{V_1}^{1/2}\ell_l}{K_{H_1}^{1/2}\ell_s} + \sinh^{-1}\frac{K_{H_1}^{1/2}\ell_s}{K_{V_1}^{1/2}\ell_l} + \frac{K_{V_1}^{1/2}\ell_l}{3K_{H_1}^{1/2}\ell_s}\left[1 + \frac{K_{H_1}^{3/2}\ell_s^3}{K_{V_1}^{3/2}\ell_l^3} - \left(1 + \frac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{3/2}\right]\right\};$$

iii. determining a vertical permeability value k_v from the value of a quantity K_{Vl} comprising one of values K_{V1} and K_{V1}/M, the aperture dimensions $2 \times \ell_s$ and $2 \times \ell_l$, the measured pressure P_f, a pressure value $\overline{P}_{pj}$ comprising one of the average pressure values $\overline{P}_{p1}$ and $\overline{P}_{p2}$, a flow rate Q_n comprising one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationships

$$K_{Vl} = \frac{4r_p[(P_{pj}^2 - P_f^2)/2P_{pj}]k_v}{Q_n\,\mu},$$
$$r_p = \sqrt{\ell_s^2/2 + \ell_l^2/2}\,.$$

15. A method of estimating permeability of an earth formation in at least one of the horizontal and vertical directions, the formation containing a formation fluid, comprising the steps of:

a. measuring a pressure P_f of the formation fluid;

b. creating a pressure disturbance in the formation fluid by displacing fluid through a first probe aperture for a first time period at a first fow rate Q_1, the first probe aperture having a circular cross-section of radius r_{p1};

c. measuring a pressure P_{p1} of the fluid substantially at the end of the first time period;

d. creating a pressure disturbance in the formation fluid by displacing fluid through a second probe aperture for a second time period at a second rate Q_2, the second probe aperture having an elongate cross section of width $2 \times \ell_s$ and length $2 \times \ell_l$;

e. measuring a pressure P_{p2} of the fluid substantially at the end of the second time period;

f. determining a value μ for viscosity of fluid in the formation; and

g. determining a value of permeability in at least one of the horizontal and vertical directions from the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1}, the measured pressure P_f, at least one of the measured pressures P_{p1} and P_{p2}, at least one of the flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation.

16. The method of claim 15, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2;

ii. determining a value of a dimensionless quantity K_{Hl} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_V representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1}; and

iii. determining a horizontal permeability value k_h from the values of quantity K_{Hl}; an aperture dimension r_{pm} comprising one of values r_{p1} and r_{p2} where r_{p2} is a function of $2 \times \ell_s$ and $2 \times \ell_l$; the measured pressure P_f; at least one of measured pressures P_{p1} and P_{p2}; at least one of flow rates Q_1 and Q_2; and the de-

termined value μ for viscosity of fluid in the formation.

17. The method of claim 15,wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2;
ii. determining a value of a dimensionless quantity K_H representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{VI} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1}; and
iii. determining a vertical permeability value k_v from the values of quantity K_{VI}; an aperture dimension r_{pm} comprising one of values r_{p1} and r_{p2} where r_{p2} is a function of $2 \times \ell_s$ and $2 \times \ell_l$; the measured pressure P_f; at least one of measured pressures P_{p1} and P_{p2}; at least one of flow rates Q_1 and Q_2; and the determined value μ for viscosity of fluid in the formation.

18. The method of claim 15, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1} in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi} F\left(\frac{\pi}{2}, \sqrt{1 - \frac{K_{V_1}}{K_{H_1}}}\right)$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_{P_2}}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} \le 1 \\ \dfrac{2r_{P_2} K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_s^2}{K_{V_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} > 1 \end{cases},$$

$$r_{P_2} = \sqrt{\ell_s^2/2 + \ell_l^2/2};$$

where F denotes the complete elliptic integral of the first kind;
iii. determining a horizontal permeability value k_h from the value of a quantity K_{HI} comprising one of quantities K_{H1} and K_{H1}/M. a value r_{pm} comprising one of values r_{p1} and r_{p2}, the measured pressure P_f, a measured pressure P_{pl} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationship

$$K_{HI} = \frac{4r_{pm}l(P_{pl} - P_f)k_h}{Q_n \mu}.$$

19. The method of claim 15, wherein step g. comprises the steps of:
i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1} - P_f)}{Q_1(P_{p2} - P_f)};$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1} in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi} F\left(\frac{\pi}{2}, \sqrt{1 - \frac{K_{V_1}}{K_{H_1}}}\right)$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_{p_2}}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} \le 1 \\ \dfrac{2r_{p_2} K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1} \ell_s^2}{K_{V_1} \ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1} \ell_l^2}{K_{H_1} \ell_s^2} > 1 \end{cases},$$

$$r_{p_2} = \sqrt{\ell_s^2/2 + \ell_l^2/2} \; ;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a vertical permeability value k_v from the values of a quantity K_{Vl} comprising one of the values K_{V1} and K_{V1}/M, a value r_{pm} comprising one of values r_{p1} and r_{p2}, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationship

$$K_{V1} = \frac{4r_{pm}[(P_{pj} - P_f)k_n}{Q_n \mu}.$$

20. The method of claim 15, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rates Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{p1}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions ℓ_s, ℓ_l and r_{p1} in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi} F\left(\frac{\pi}{2}, \sqrt{1 - \frac{K_{V_1}}{K_{H_1}}}\right)$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_{p_2}}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \le 1 \\ \dfrac{2r_{p_2}K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases},$$

$$r_{p_2} = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a horizontal permeability value k_h from the values of a quantity K_{Hl} comprising one of quantities K_{H1} and K_{H1}/M, a value r_{pm} comprising one of values r_{p1} and r_{p2}, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationship

$$K_{H1} = \frac{4r_{pm}[(P_{pj}^2 - P_f^2)/2P_{pj}]k_h}{Q_n\,\mu}.$$

pressure P_f, the measured pressure P_{p1}, the flow rate Q_1, and the determined value μ for viscosity of fluid in the formation in accordance with the relationship

$$K_{H1} = \frac{4r_{p1}[(P_{p1}^2 - P_f^2)/2P_{p1}]k_h}{Q_1\,\mu}.$$

21. The method of claim 15, wherein step g. comprises the steps of:

i. calculating a measurement factor M from the measured pressures P_f, P_{p1} and P_{p2} and from the flow rate Q_1 and Q_2 in accordance with the relationship

$$M = \frac{Q_2(P_{p1}^2 - P_f^2)P_{p2}}{Q_1(P_{p2}^2 - P_f^2)P_{p1}}.$$

ii. determining a value of a dimensionless quantity K_{H1} representative of the horizontal permeability of the formation and a value of a dimensionless quantity K_{V1} representative of the vertical permeability of the formation, based on the calculated measurement factor M and the aperture dimensions $2 \times \ell_s$, $2 \times \ell_l$ and r_{p1} in accordance with the relationships

$$K_{H_1} = \frac{2}{\pi} F\left(\frac{\pi}{2}, \sqrt{1 - \frac{K_{V_1}}{K_{H_1}}}\right)$$

$$\frac{K_{H_1}}{M} = \begin{cases} \dfrac{2r_{p_2}}{\pi \ell_s} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} \leq 1 \\ \dfrac{2r_{p_2}K_{H_1}^{1/2}}{\pi \ell_l K_{V_1}^{1/2}} F\left(\dfrac{\pi}{2}, \left(1 - \dfrac{K_{H_1}\ell_s^2}{K_{V_1}\ell_l^2}\right)^{1/2}\right) & \text{for } \dfrac{K_{V_1}\ell_l^2}{K_{H_1}\ell_s^2} > 1 \end{cases},$$

$$r_{p_2} = \sqrt{\ell_s^2/2 + \ell_l^2/2} \;;$$

where F denotes the complete elliptic integral of the first kind;

iii. determining a vertical permeability value k_v from the values of a quantity K_{Vl} comprising one of the values K_{V1} and K_{V1}/M, a value r_{pm} comprising one of values r_{p1} and r_{p2}, the measured pressure P_f, a measured pressure P_{pj} comprising one of measured pressures P_{p1} and P_{p2}, a flow rate Q_n comprising one of flow rates Q_1 and Q_2, and the determined value μ for viscosity of fluid in the formation in accordance with the relationship

$$K_{V1} = \frac{4r_{pm}[(P_{pj}^2 - P_f^2)/2P_{pj}]k_v}{Q_n \mu}.$$

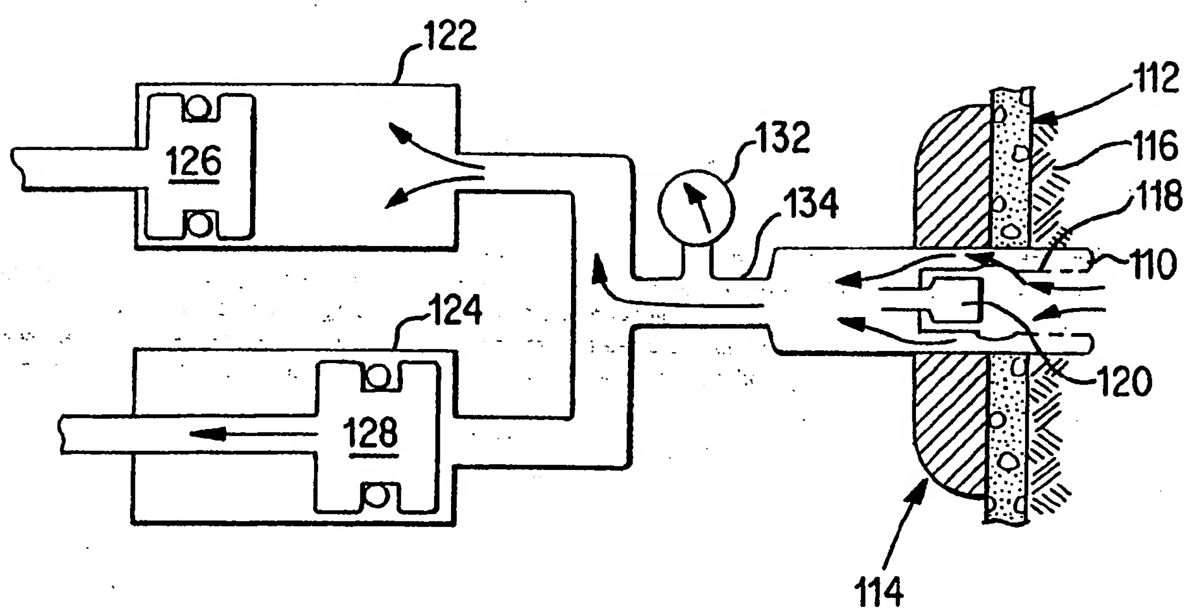


FIG. 1 PRIOR ART

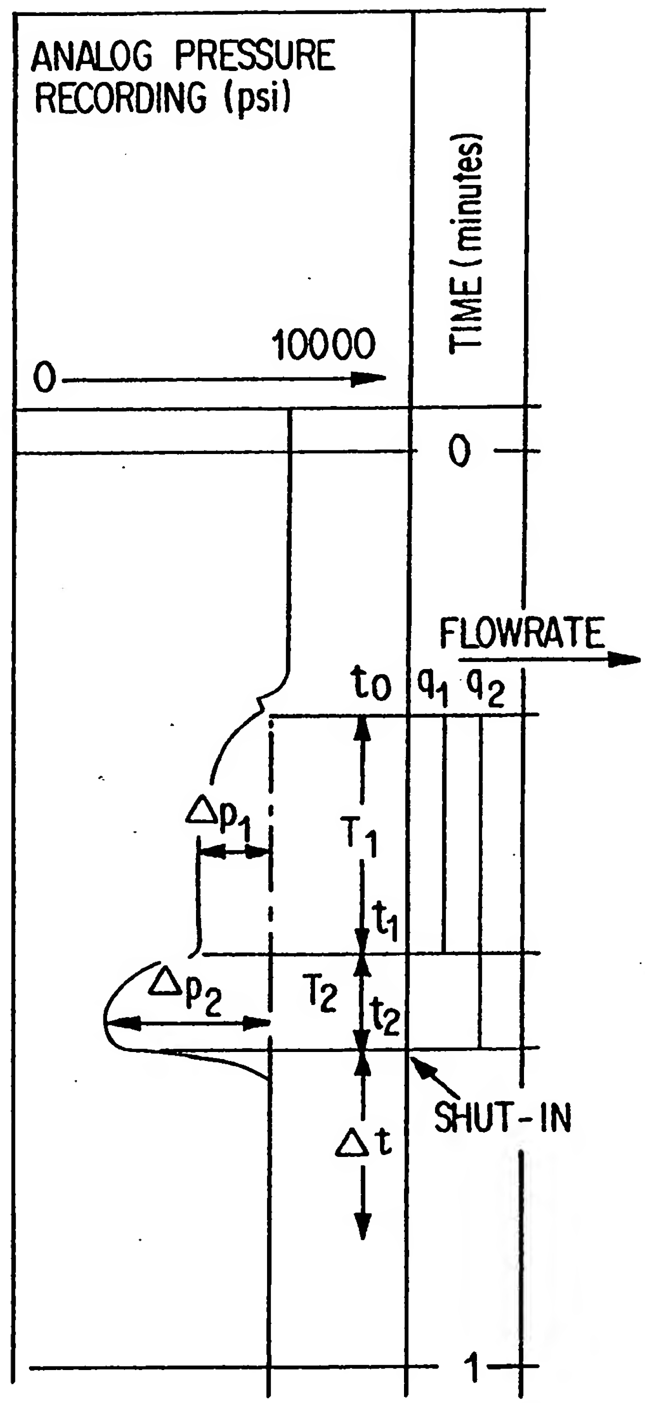


FIG. 2 PRIOR ART

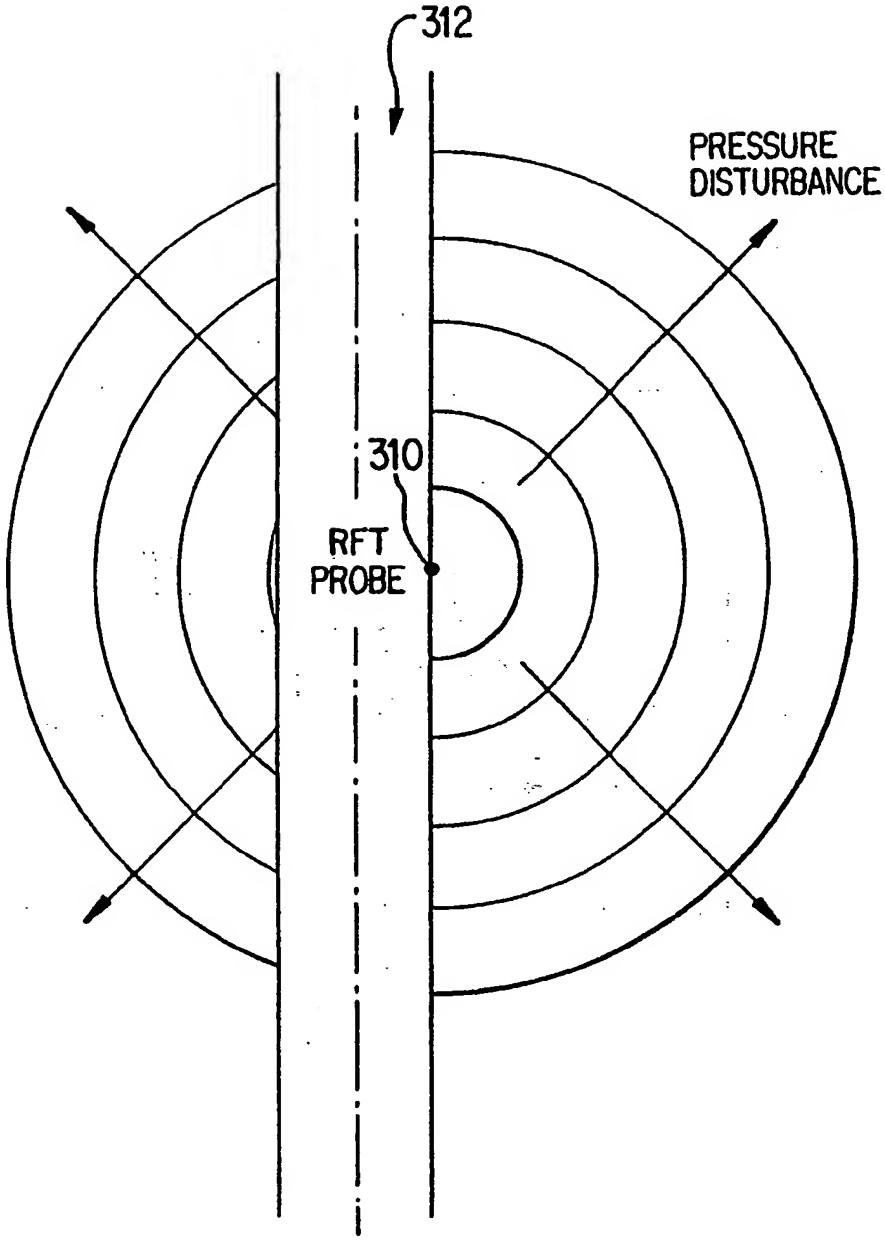


FIG. 3 PRIOR ART

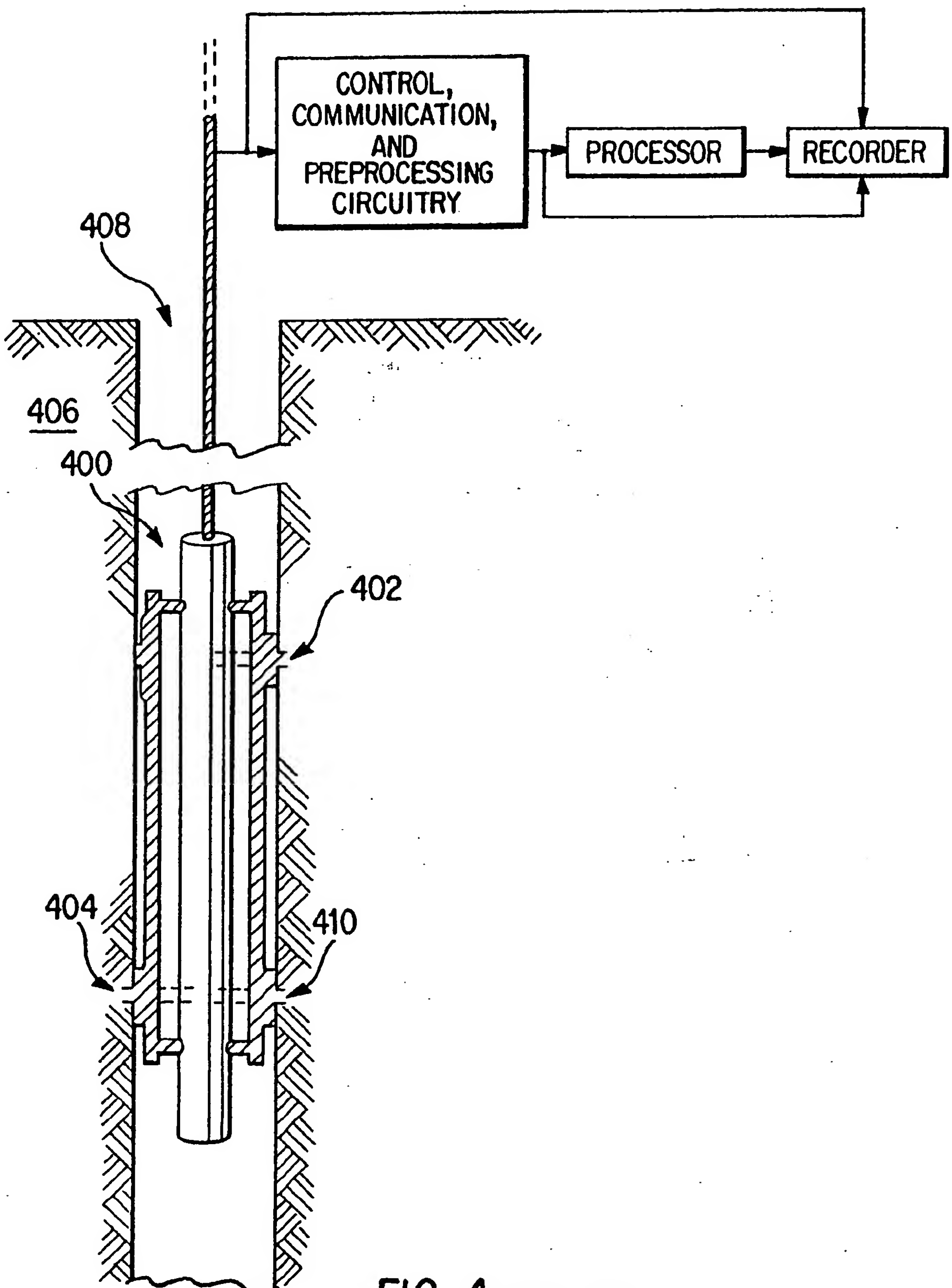


FIG. 4 PRIOR ART

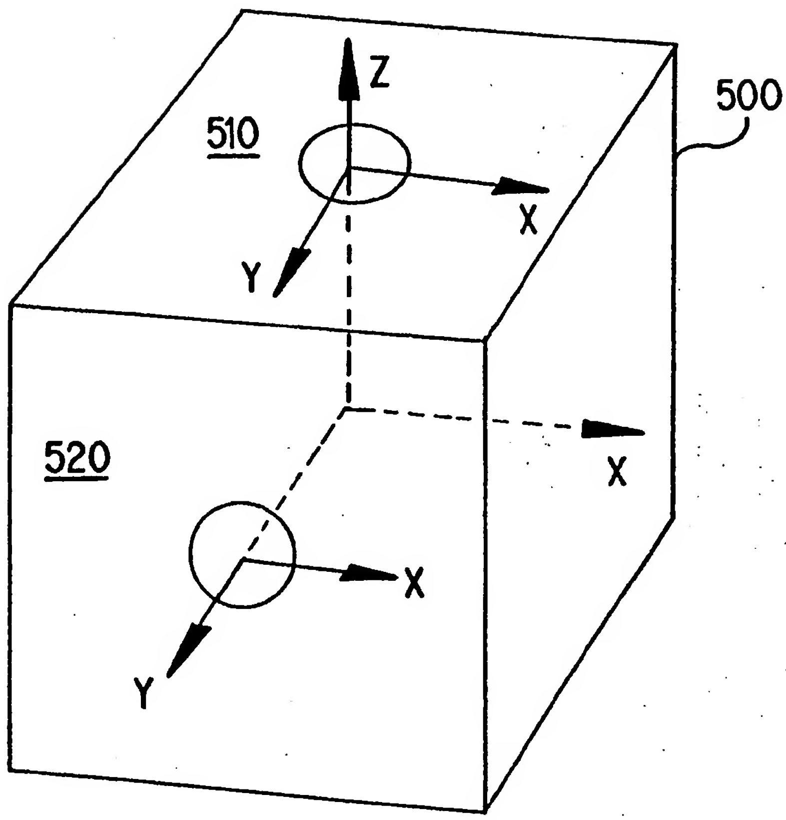


FIG. 5 PRIOR ART

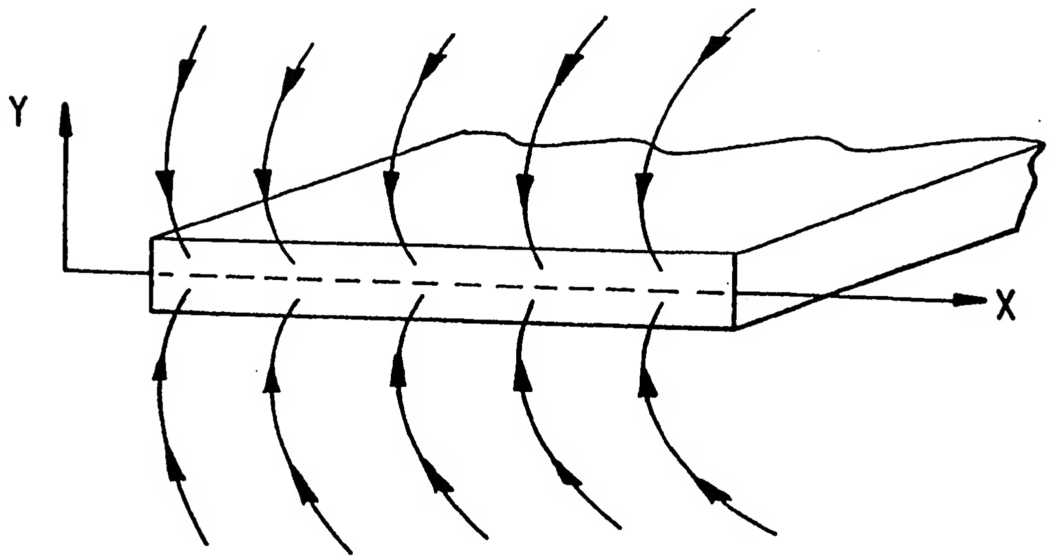


FIG. 6

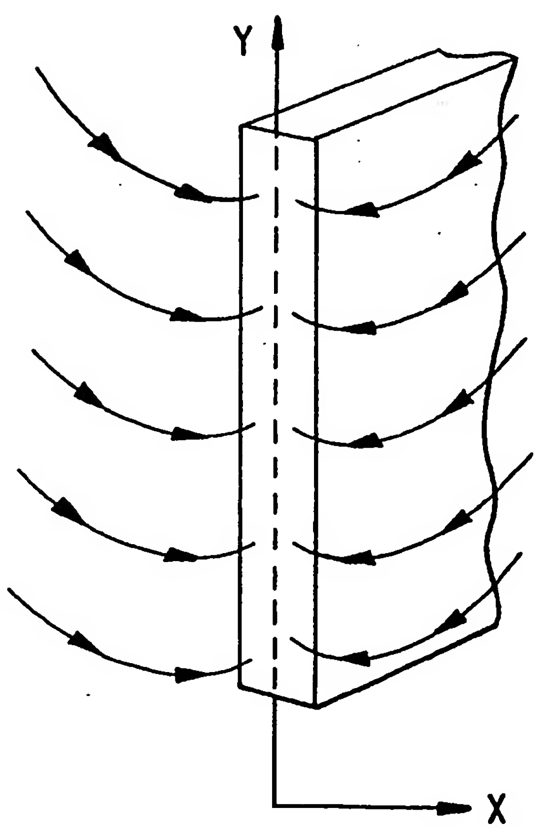


FIG. 7

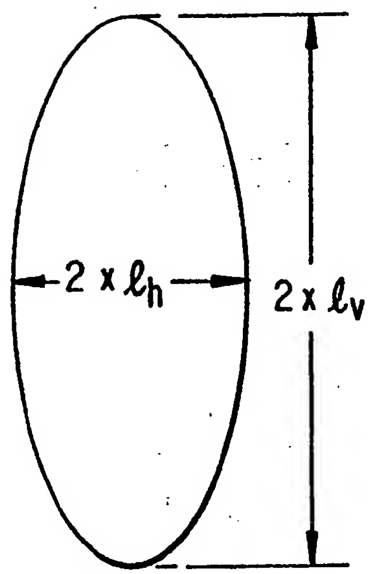
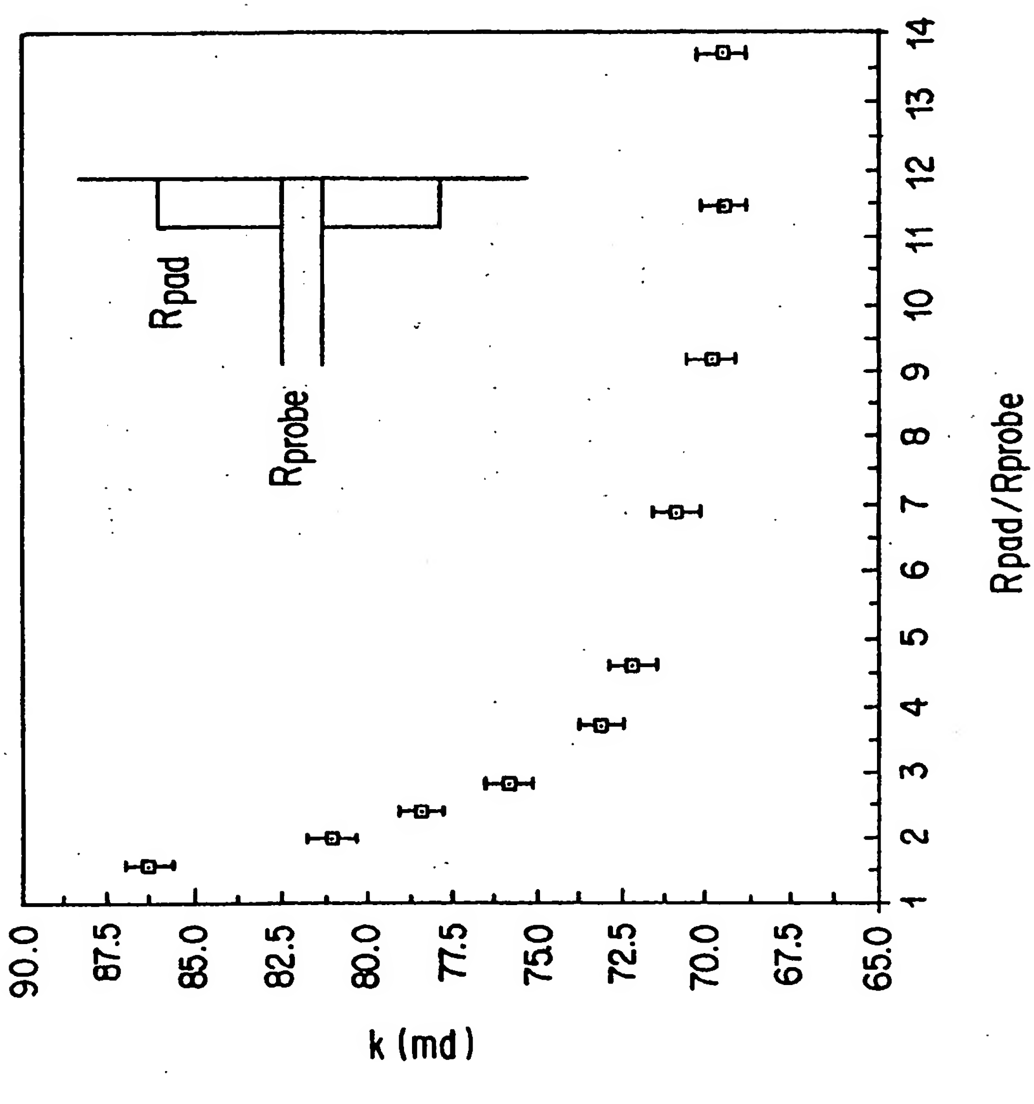


FIG. 8


Rpad
Rprobe
k (md)
90.0
87.5
85.0
82.5
80.0
77.5
75.0
72.5
70.0
67.5
65.0
Rpad/Rprobe
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2
3
4
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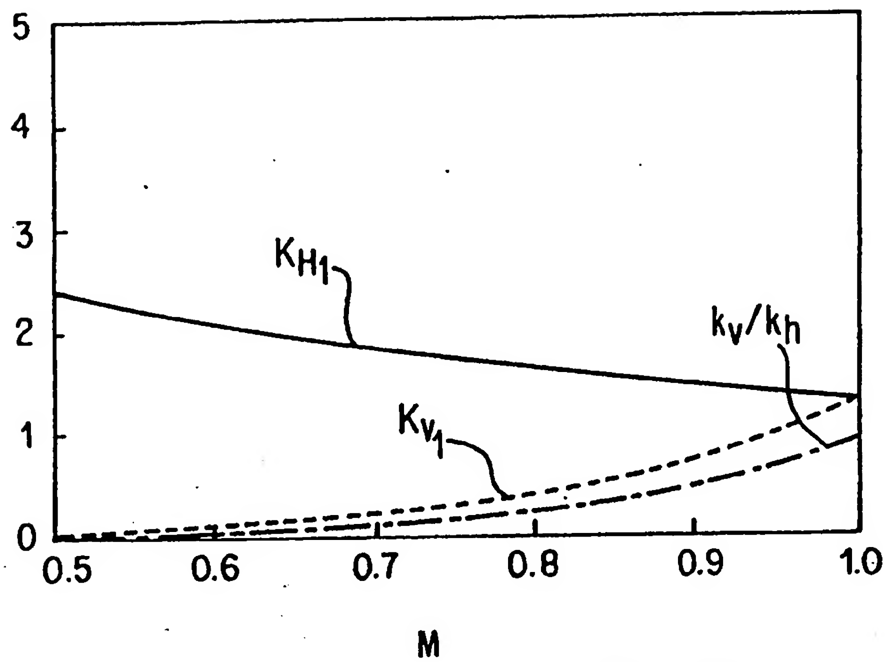
6
7
8
9
10
11
12
13
14

FIG. 9

M	K_{H_1}	K_{V_1}	K_{H_2}	K_{V_2}	k_h/k_v
1.0000	1.385	1.385	1.385	1.385	1
0.8838	1.540	0.7699	1.742	0.8711	2
0.8231	1.631	0.5438	1.982	0.6607	3
0.7832	1.697	0.4241	2.166	0.5415	4
0.7541	1.747	0.3495	2.317	0.4634	5
0.7314	1.789	0.2981	2.446	0.4076	6
0.7130	1.824	0.2606	2.558	0.3654	7
0.6977	1.854	0.2318	2.658	0.3322	8
0.6846	1.881	0.2090	2.748	0.3053	9
0.6732	1.905	0.1905	2.830	0.2830	10
0.6631	1.927	0.1752	2.906	0.2642	11
0.6542	1.947	0.1622	2.976	0.2480	12
0.6461	1.965	0.1512	3.041	0.2340	13
0.6388	1.982	0.1416	3.103	0.2216	14
0.6322	1.998	0.1332	3.160	0.2107	15
0.6260	2.013	0.1258	3.215	0.2009	16
0.6204	2.027	0.1192	3.267	0.1922	17
0.6151	2.040	0.1133	3.316	0.1842	18
0.6102	2.052	0.1080	3.363	0.1770	19
0.6057	2.064	0.1032	3.407	0.1704	20
0.6014	2.075	0.09880	3.450	0.1643	21
0.5974	2.086	0.09480	3.491	0.1587	22
0.5935	2.096	0.09112	3.531	0.1535	23
0.5899	2.105	0.08773	3.569	0.1487	24
0.5865	2.115	0.08459	3.606	0.1442	25
0.6732	1.905	0.1905	2.830	0.2830	10
0.6057	2.064	0.1032	3.407	0.1704	20
0.5718	2.157	0.07188	3.772	0.1257	30
0.5500	2.222	0.05556	4.041	0.1010	40
0.5342	2.274	0.04547	4.256	0.0851	50
0.5221	2.315	0.03859	4.435	0.0739	60
0.5124	2.351	0.03358	4.588	0.0655	70
0.5043	2.381	0.02977	4.722	0.0590	80
0.4974	2.408	0.02676	4.842	0.0538	90
0.4914	2.433	0.02433	4.950	0.0495	100

FIG.10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0.5
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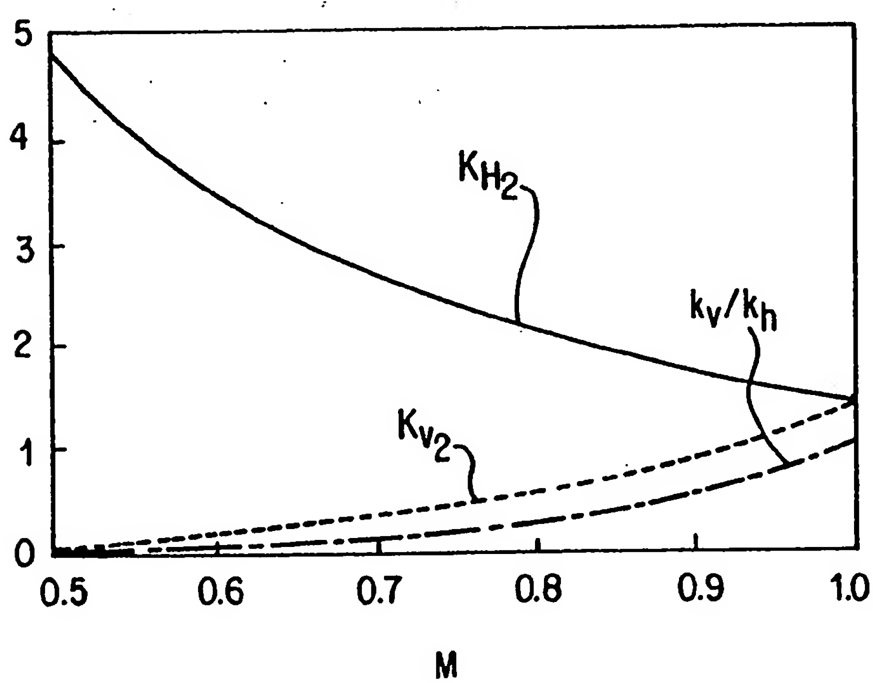
1.0
M
K_{H1}
K_{V1}
k_v/k_h

FIG. 11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0.5
0.6
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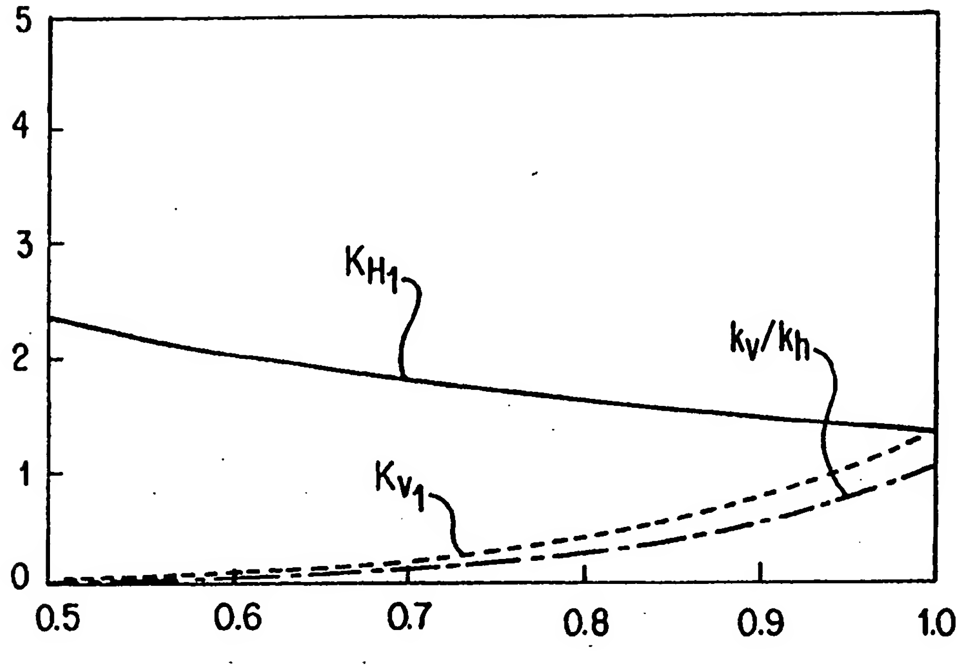
0.8
0.9
1.0
M
K_{H2}
K_{V2}
k_v/k_h

FIG. 12

M	K_{H_1}	K_{V_1}	K_{H_2}	K_{V_2}	k_h/k_v
1.0000	2.697	2.697	2.697	2.697	1
0.7939	2.853	1.427	3.594	1.797	2
0.6939	2.945	0.9815	4.244	1.145	3
0.6308	3.009	0.7523	4.771	1.193	4
0.5859	3.060	0.6119	5.222	1.004	5
0.5517	3.101	0.5168	5.620	0.9366	6
0.5244	3.135	0.4479	5.978	0.8540	7
0.5019	3.165	0.3957	6.306	0.7883	8
0.4829	3.192	0.3546	6.609	0.7344	9
0.4666	3.216	0.3216	6.892	0.6892	10
0.4523	3.237	0.2943	7.157	0.6507	11
0.4396	3.257	0.2714	7.408	0.6173	12
0.4283	3.275	0.2519	7.645	0.5881	13
0.4181	3.291	0.2351	7.872	0.5623	14
0.4089	3.307	0.2205	8.088	0.5392	15
0.4004	3.321	0.2076	8.295	0.5185	16
0.3926	3.335	0.1962	8.494	0.4997	17
0.3854	3.348	0.1860	8.686	0.4826	18
0.3787	3.360	0.1768	8.871	0.4669	19
0.3725	3.372	0.1686	9.050	0.4525	20
0.3667	3.383	0.1611	9.224	0.4392	21
0.3613	3.393	0.1542	9.392	0.4269	22
0.3561	3.403	0.1480	9.555	0.4154	23
0.3513	3.413	0.1422	9.714	0.4047	24
0.3467	3.422	0.1369	9.868	0.3947	25
0.4666	3.216	0.3216	6.892	0.6892	10
0.3725	3.372	0.1686	9.050	0.4525	20
0.3271	3.463	0.1154	10.59	0.3529	30
0.2985	3.528	0.08819	11.82	0.2954	40
0.2783	3.578	0.07156	12.86	0.2572	50
0.2628	3.619	0.06031	13.77	0.2295	60
0.2505	3.654	0.05219	14.58	0.2084	70
0.2404	3.684	0.04604	15.33	0.1916	80
0.2318	3.710	0.04122	16.01	0.1778	90
0.2244	3.734	0.03734	16.64	0.1664	100

FIG.13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K_{H_1}
k_v/k_h
K_{v_1}
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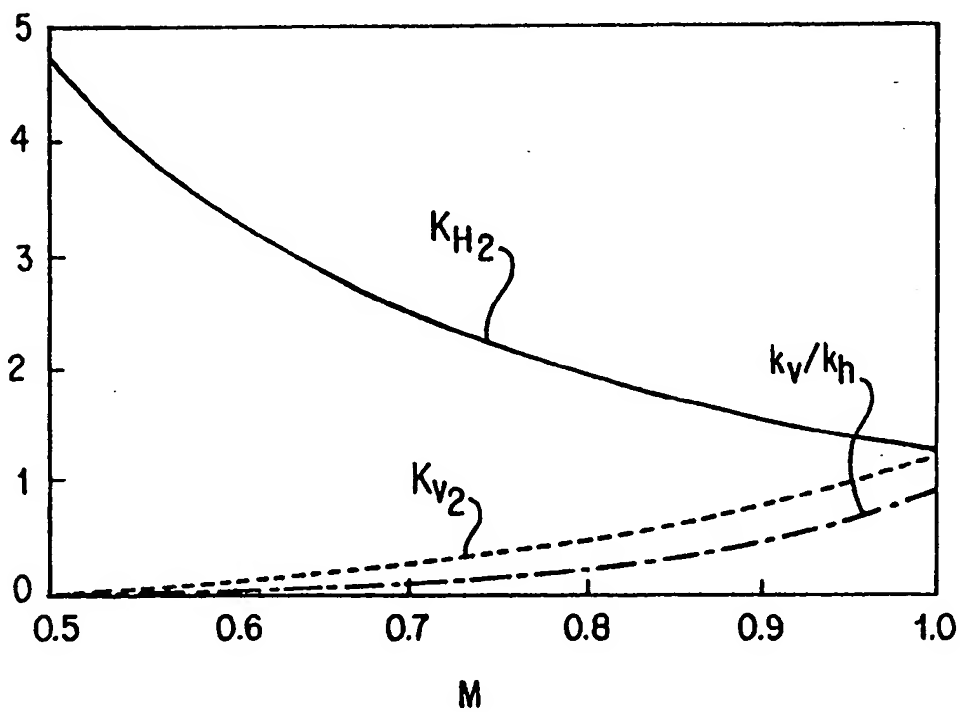
0.9
1.0
M

FIG.14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1
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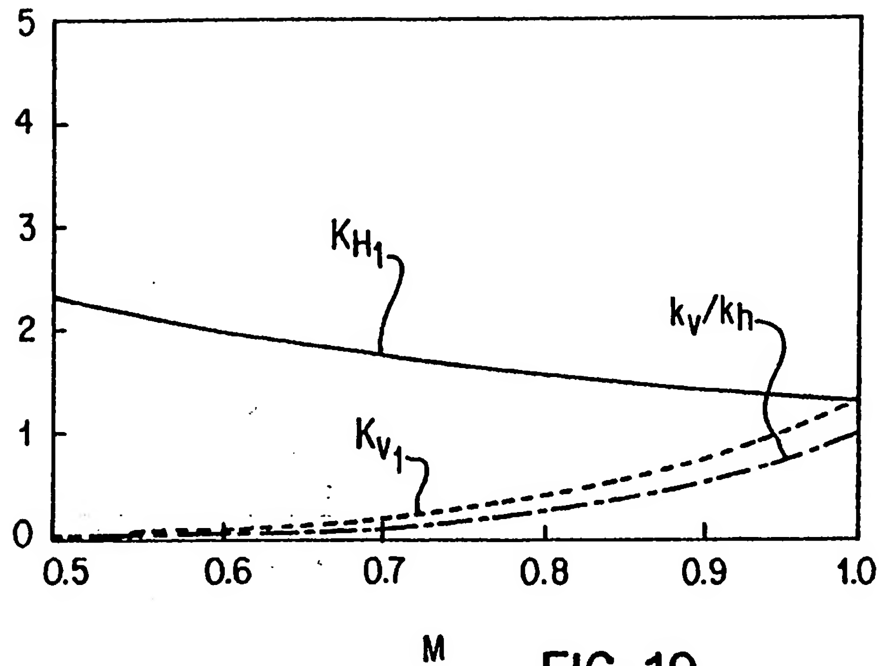
K_{H_2}
k_v/k_h
K_{v_2}
0.5
0.6
0.7
0.8
0.9
1.0
M

FIG.15

M	K_{H_1}	K_{V_1}	K_{H_2}	K_{V_2}	k_h/k_v
1.000	1.316	1.316	1.316	1.316	1
0.8871	1.467	0.7335	1.654	0.8268	2
0.8280	1.556	0.5187	1.880	0.6265	3
0.7890	1.620	0.4050	2.053	0.5133	4
0.7605	1.670	0.3339	2.195	0.4391	5
0.7383	1.710	0.2850	2.317	0.3861	6
0.7202	1.745	0.2492	2.423	0.3461	7
0.7051	1.775	0.2218	2.517	0.3146	8
0.6922	1.801	0.2001	2.602	0.2891	9
0.6810	1.825	0.1825	2.680	0.2680	10
0.6711	1.846	0.1678	2.751	0.2501	11
0.6623	1.866	0.1555	2.817	0.2348	12
0.6543	1.884	0.1449	2.879	0.2215	13
0.6471	1.900	0.1357	2.937	0.2098	14
0.6405	1.916	0.1277	2.991	0.1994	15
0.6345	1.931	0.1207	3.043	0.1902	16
0.6289	1.944	0.1144	3.092	0.1819	17
0.6237	1.957	0.1087	3.138	0.1743	18
0.6189	1.969	0.1037	3.182	0.1675	19
0.6143	1.981	0.09905	3.225	0.1612	20
0.6101	1.992	0.09486	3.265	0.1555	21
0.6061	2.003	0.09103	3.304	0.1502	22
0.6023	2.013	0.08751	3.342	0.1453	23
0.5987	2.022	0.08426	3.378	0.1407	24
0.5954	2.032	0.08126	3.412	0.1365	25
0.6810	1.825	0.1825	2.680	0.2680	10
0.6143	1.981	0.09905	3.225	0.1612	20
0.5807	2.073	0.06910	3.570	0.1190	30
0.5590	2.138	0.05345	3.825	0.09562	40
0.5433	2.189	0.04378	4.029	0.08057	50
0.5313	2.230	0.03717	4.198	0.06997	60
0.5215	2.265	0.03236	4.344	0.06206	70
0.5134	2.296	0.02870	4.472	0.05590	80
0.5065	2.323	0.02581	4.586	0.05095	90
0.5005	2.347	0.02347	4.689	0.04689	100

FIG.18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K_{H_1}
k_v/k_h
K_{v_1}
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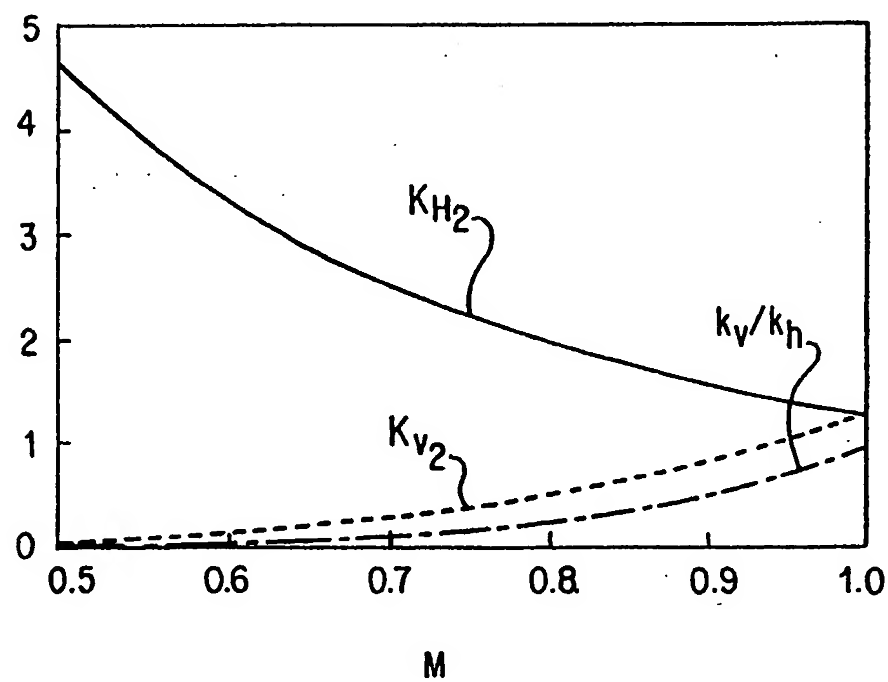
0.9
1.0
M

FIG. 19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k_v/k_h
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0.6
0.7
0.8
0.9
1.0
M

FIG. 20

M	K_{H_1}	K_{V_1}	K_{H_2}	K_{V_2}	k_h/k_v
0.7222	1.000	1.0000	1.385	1.385	1
0.6775	1.180	0.5902	1.742	0.8711	2
0.6517	1.292	0.4306	1.982	0.6607	3
0.6338	1.373	0.3432	2.166	0.5415	4
0.6202	1.437	0.2874	2.317	0.4634	5
0.6093	1.490	0.2483	2.446	0.4076	6
0.6002	1.535	0.2193	2.558	0.3654	7
0.5925	1.575	0.1968	2.658	0.3322	8
0.5858	1.610	0.1789	2.748	0.3053	9
0.5799	1.641	0.1641	2.830	0.2830	10
0.5747	1.670	0.1518	2.906	0.2642	11
0.5699	1.696	0.1413	2.976	0.2480	12
0.5656	1.720	0.1323	3.041	0.2340	13
0.5617	1.743	0.1245	3.103	0.2216	14
0.5581	1.764	0.1176	3.160	0.2107	15
0.5547	1.783	0.1115	3.215	0.2009	16
0.5516	1.802	0.1060	3.267	0.1922	17
0.5487	1.819	0.1011	3.316	0.1842	18
0.5459	1.836	0.09662	3.363	0.1770	19
0.5434	1.852	0.09258	3.407	0.1704	20
0.5410	1.866	0.08888	3.450	0.1643	21
0.5387	1.881	0.08549	3.491	0.1587	22
0.5365	1.894	0.08237	3.531	0.1535	23
0.5345	1.908	0.07948	3.569	0.1487	24
0.5325	1.920	0.07680	3.606	0.1442	25
0.5799	1.641	0.1641	2.830	0.2830	10
0.5434	1.852	0.09258	3.407	0.1704	20
0.5240	1.976	0.06588	3.772	0.1257	30
0.5112	2.066	0.05164	4.041	0.1010	40
0.5017	2.135	0.04271	4.256	0.08511	50
0.4944	2.192	0.03654	4.434	0.07391	60
0.4884	2.241	0.03201	4.588	0.06554	70
0.4833	2.283	0.02853	4.722	0.05903	80
0.4790	2.320	0.02577	4.842	0.05380	90
0.4753	2.353	0.02353	4.950	0.04950	100

FIG.21

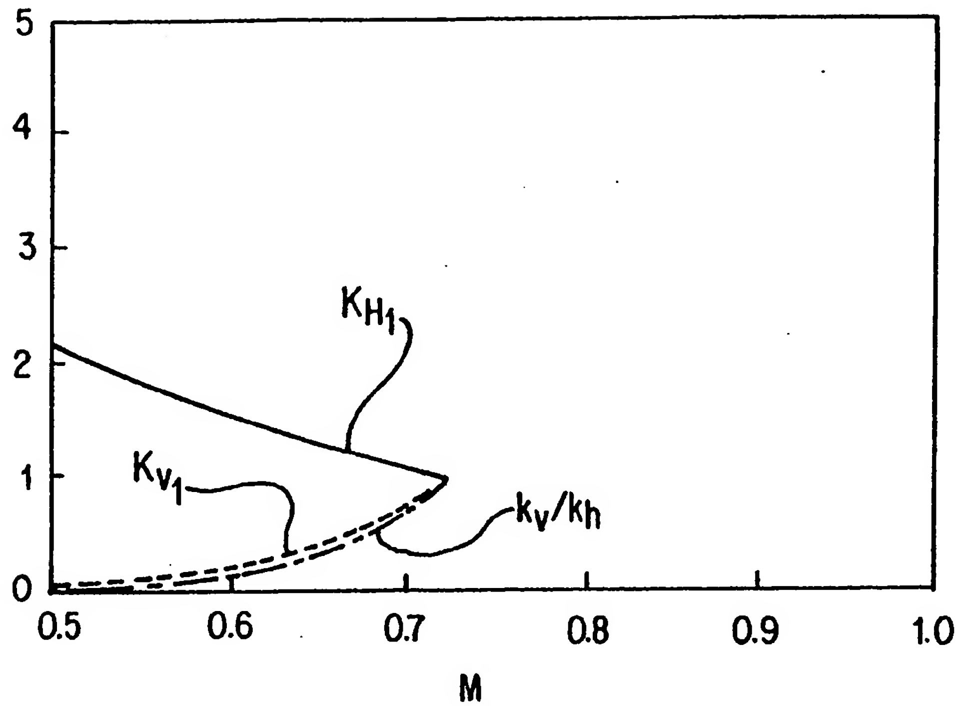
5
4
3
2
1
0
0.5
0.6
0.7
0.8
0.9
1.0
M
K_{H_1}
K_{V_1}
k_V/k_h

FIG. 22

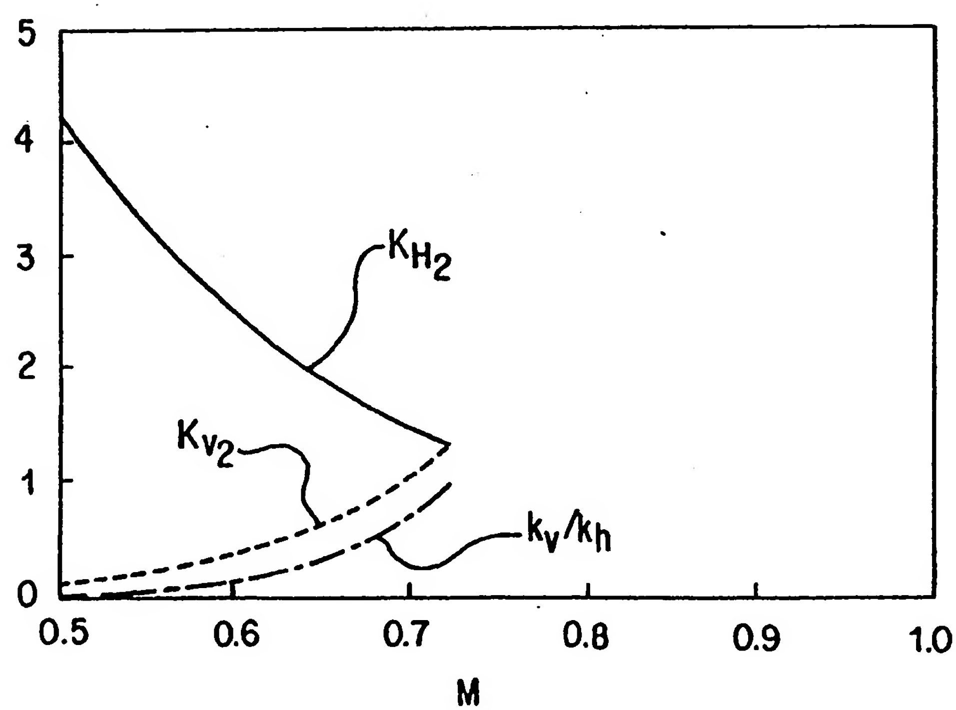
5
4
3
2
1
0
0.5
0.6
0.7
0.8
0.9
1.0
M
K_{H_2}
K_{V_2}
k_V/k_h

FIG. 23